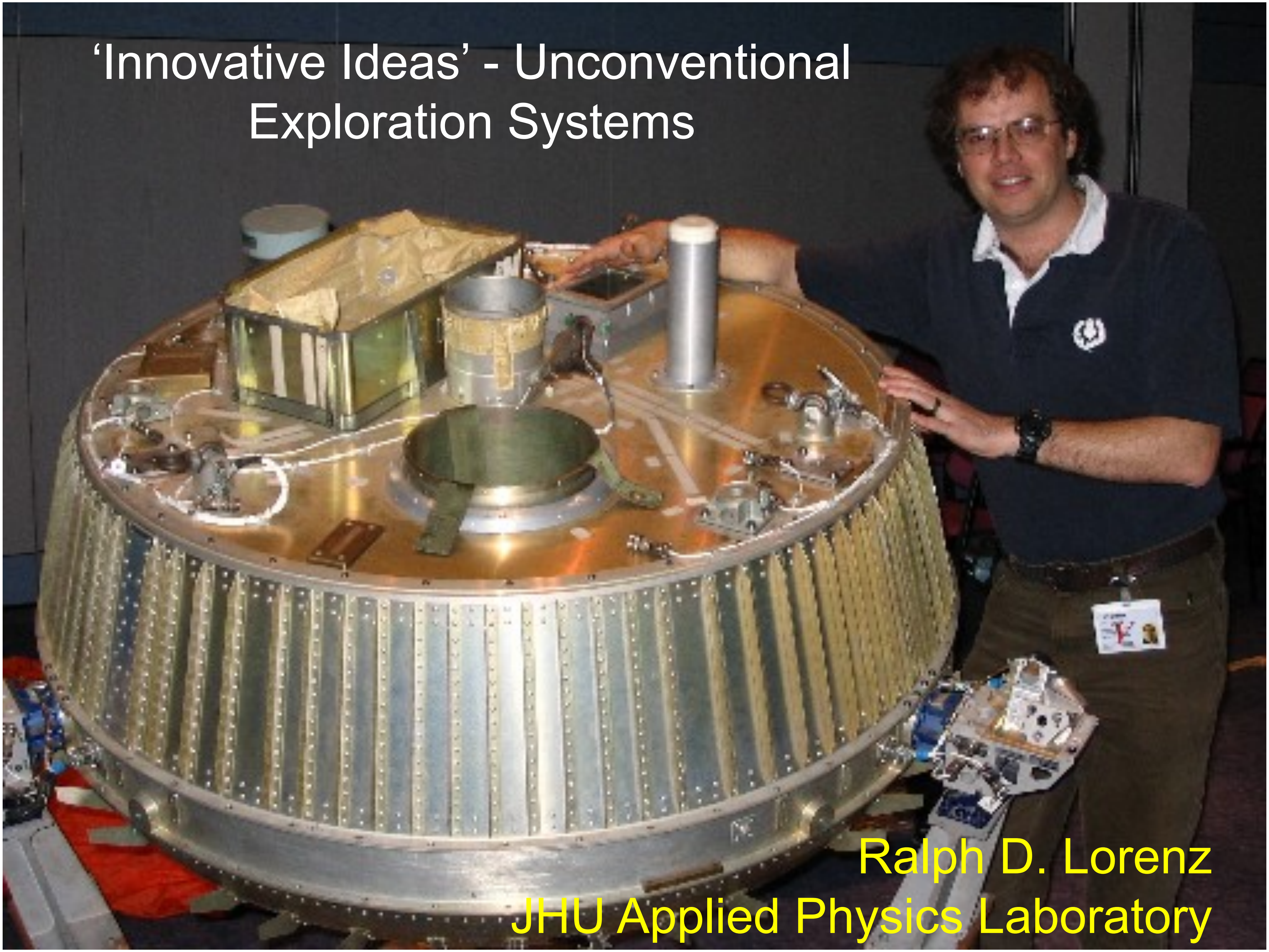
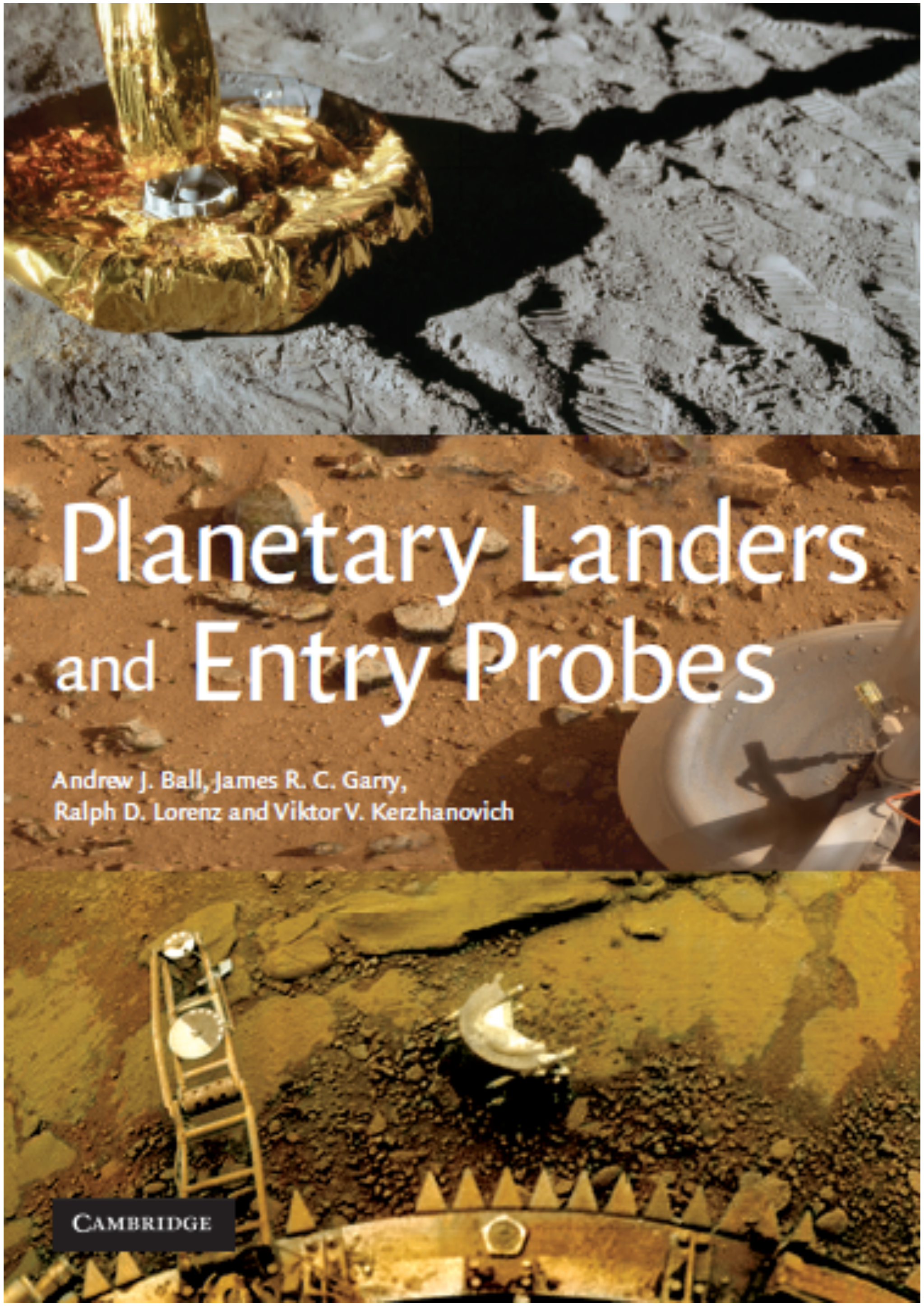
‘Innovative Ideas’ - Unconventional Exploration Systems



Ralph D. Lorenz
JHU Applied Physics Laboratory



General Observations

Lake Systems

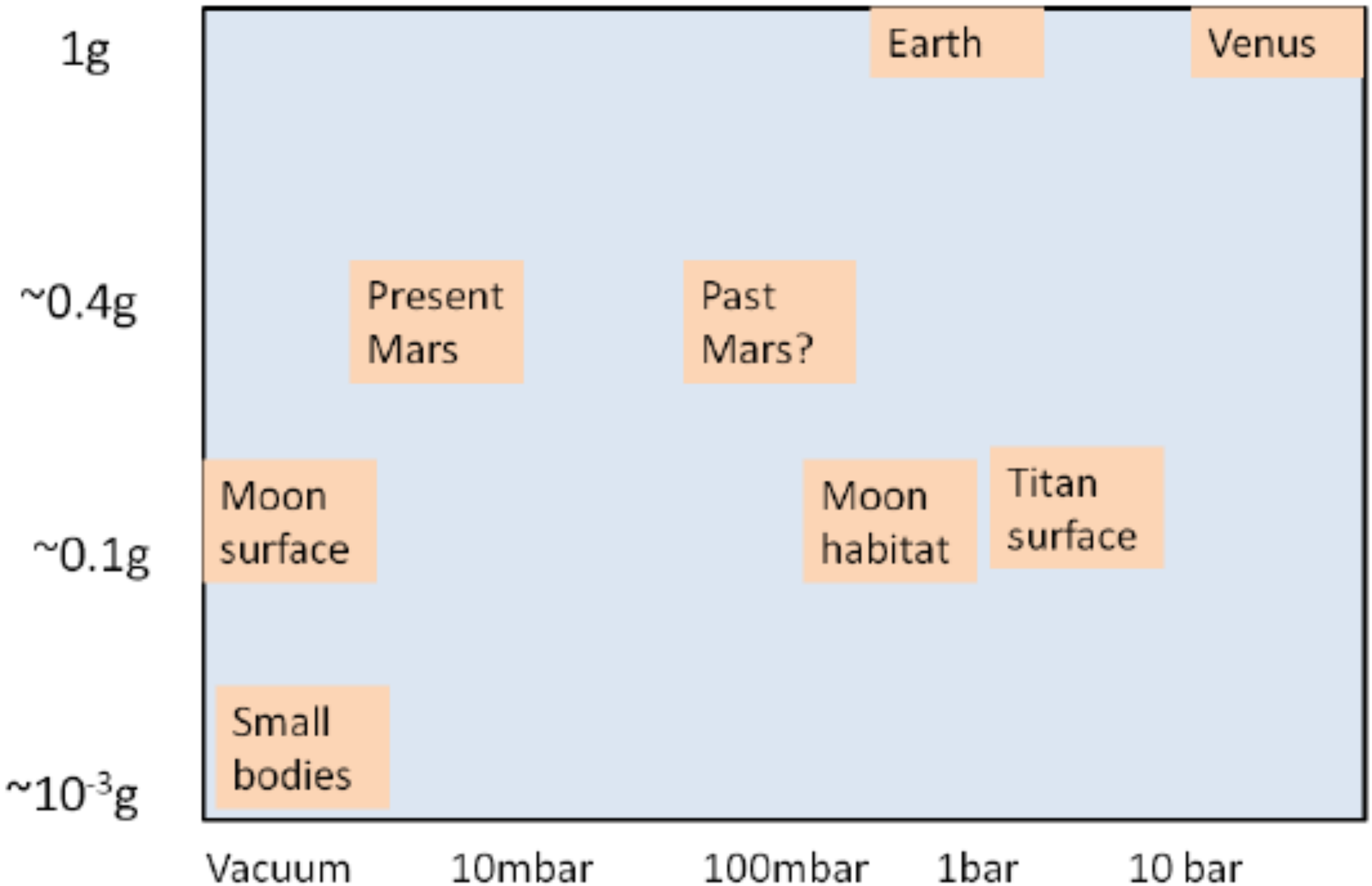
Penetrators

Tumbleweed

Samara

Balloon / Airship / Airplane / Helicopter tradeoff

Micro-vehicles


1g
~0.4g
~0.1g
~10-3g
Earth
Venus
Present Mars
Past Mars?
Moon surface
Moon habitat
Titan surface
Small bodies
Vacuum
10mbar
100mbar
1bar
10 bar

100kg Lithium battery

1kg Lithium battery

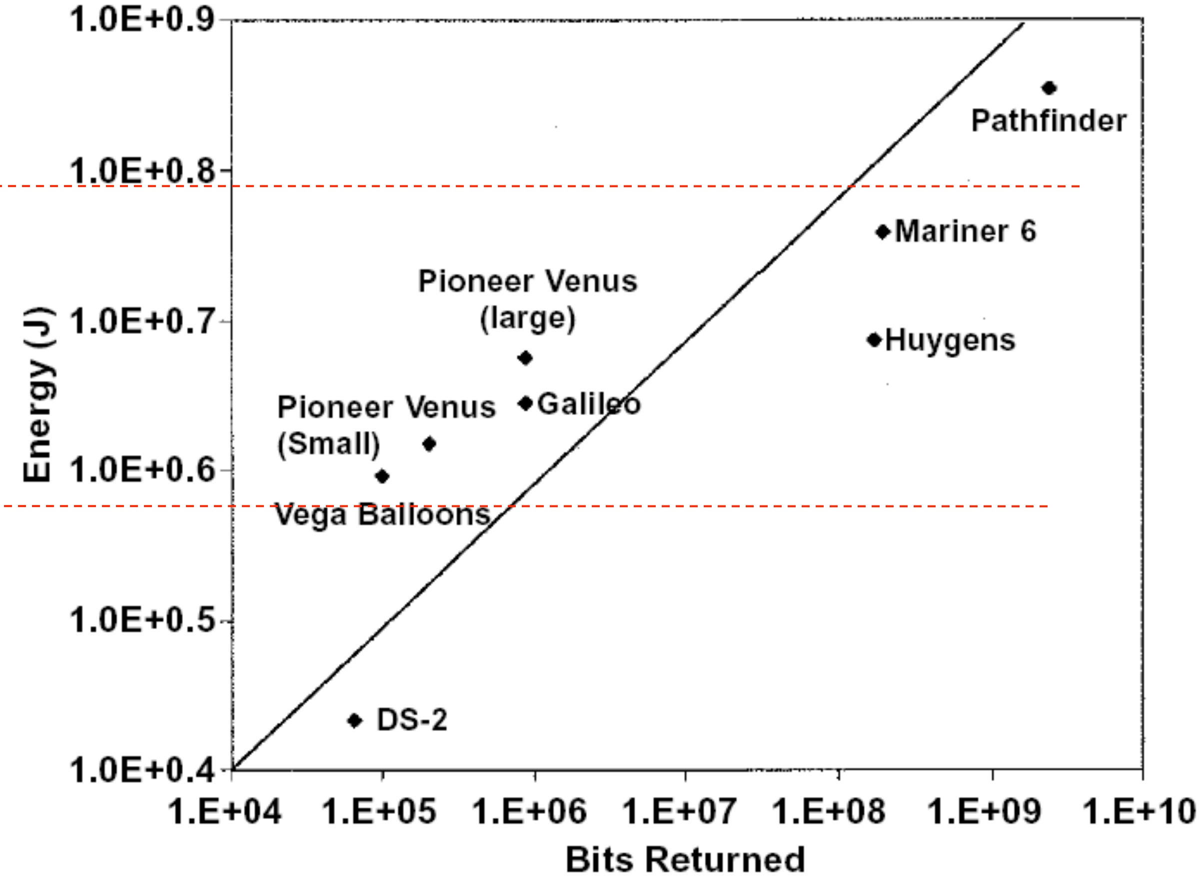


Fig. 6 Data return volume for planetary missions plotted against mission energy budget, data from A. Wilson, Solar System Log, Janes (1987) and other sources. The line shows a 1 J/bit relationship, which appears to be a good zeroth-order metric.

It's all about the data!

1 J = 1 bit
(to a few orders of magnitude….)

Data needed for valuable science increment depends on target and instrument type.

Lorenz, Journal of the British Interplanetary Society, 2000

ADVANCED EXPLORATION VEHICLES TEND NOT TO FLY AS STANDALONE PLANETARY MISSIONS

Why -

Risks not well understood. Risk aversion argues to fly what is known
Science opportunities not well understood, so science pull is not strong (remedy by seed science studies)

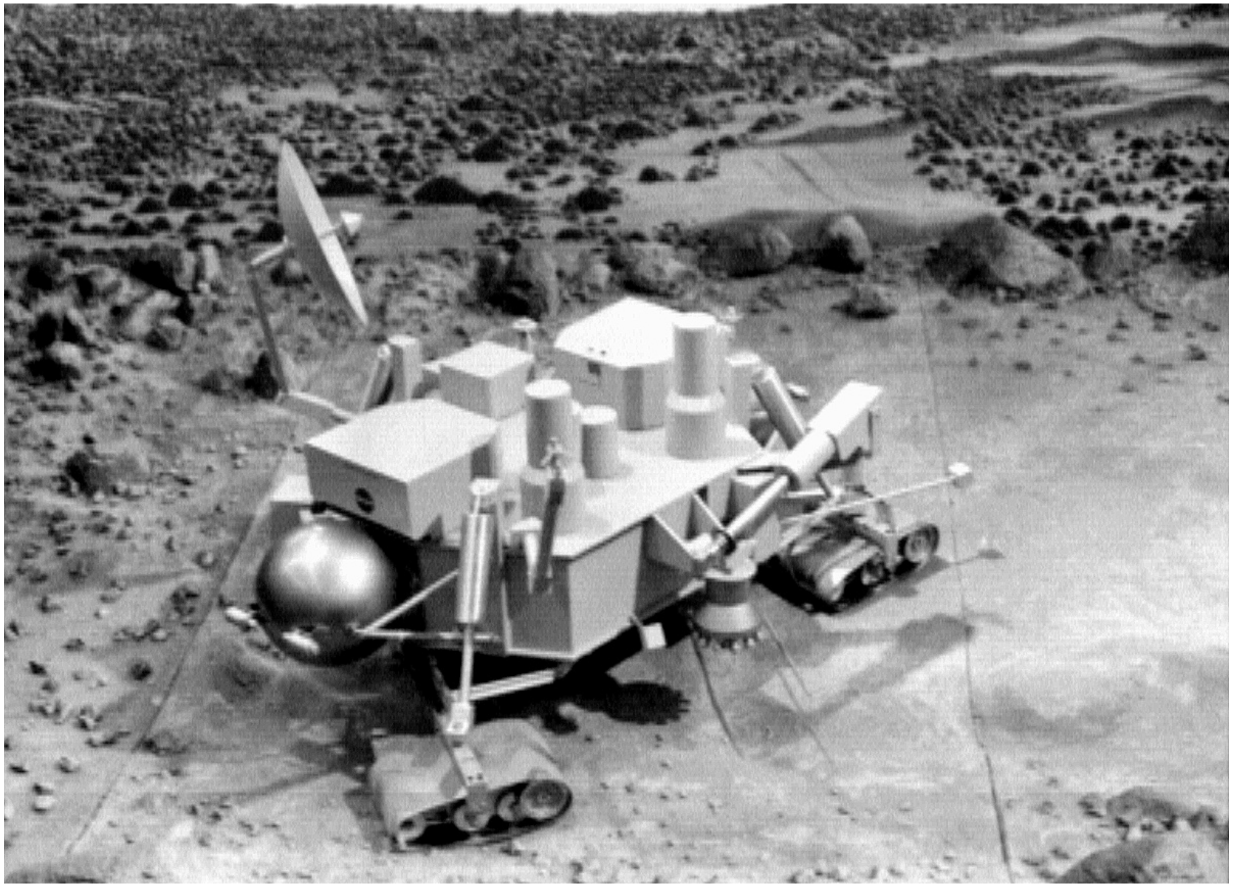
DS-2 Mars Microprobes - piggyback on Mars Polar Lander

VEGA Balloons - piggyback on Halley Flyby/Venus Lander

Sojourner Rover - piggyback on Pathfinder lander

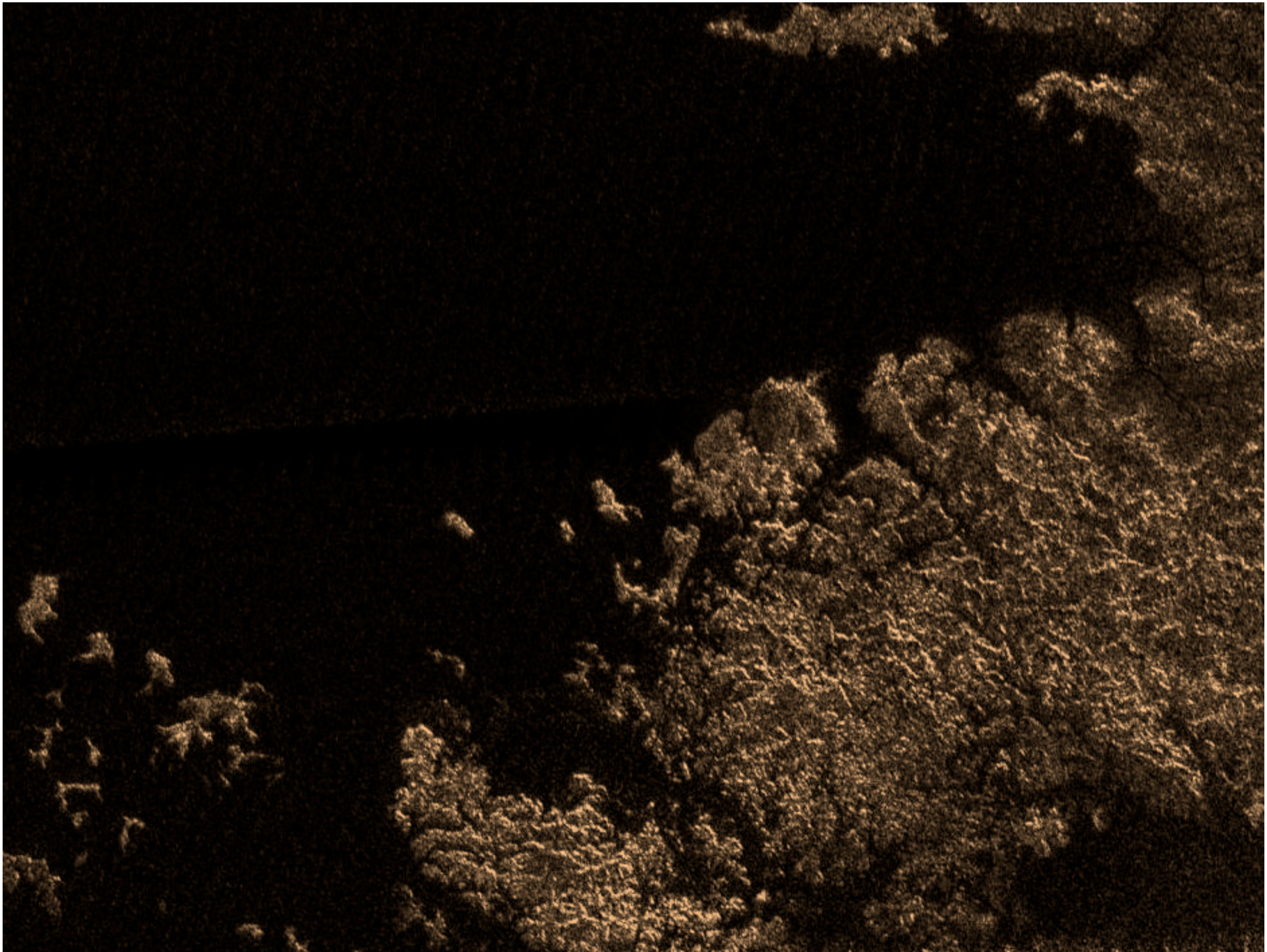
PLUTO Mole - piggyback on Beagle Lander

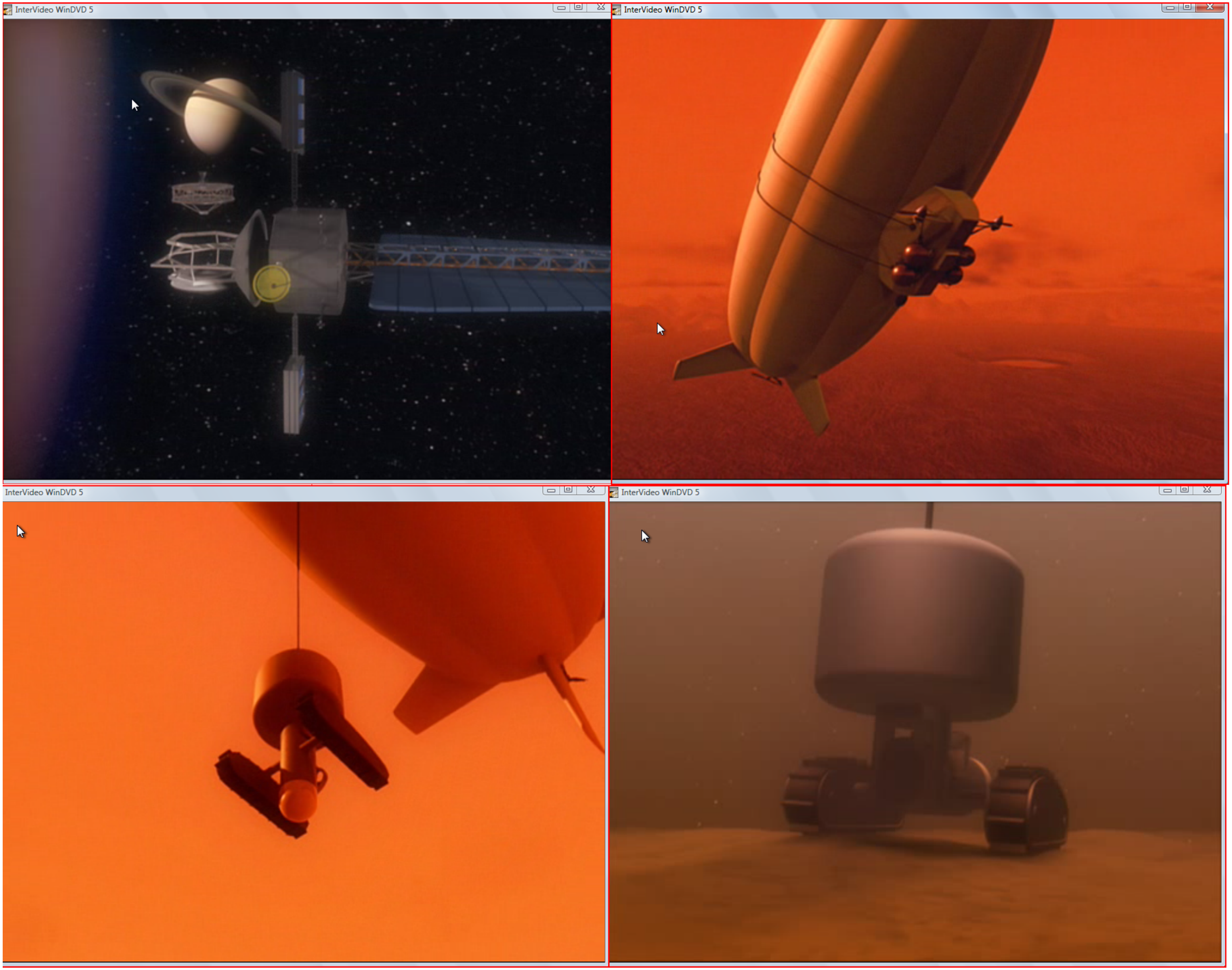
ADVANCED EXPLORATION VEHICLES TEND NOT TO FLY AS STANDALONE PLANETARY MISSIONS

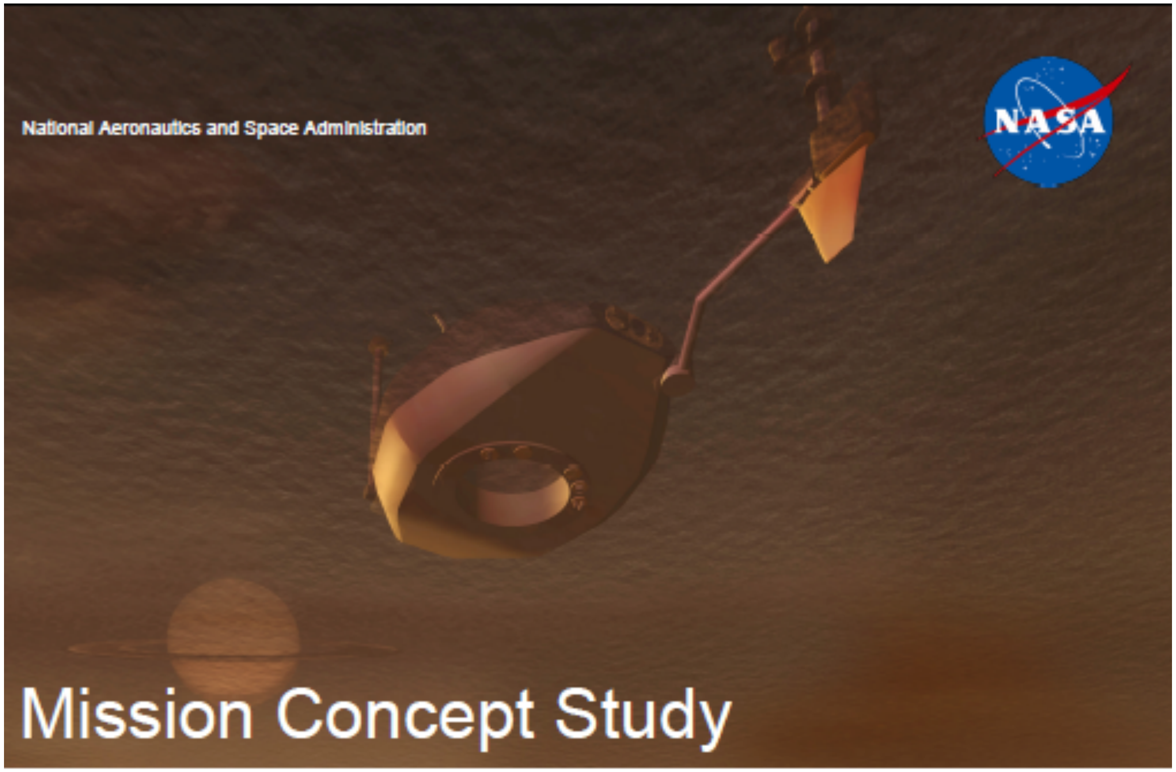


Who cares why. It is an empirical fact. Large, capable Mars science rover ('Viking 3') looked good in 1976, but it took MFE/Sojourner and 2xMER to get there

To live within this reality, balloons/moles/airplanes etc. are easier to sell (rightly or wrongly) as a subsidiary element, unless science pull is overwhelming.

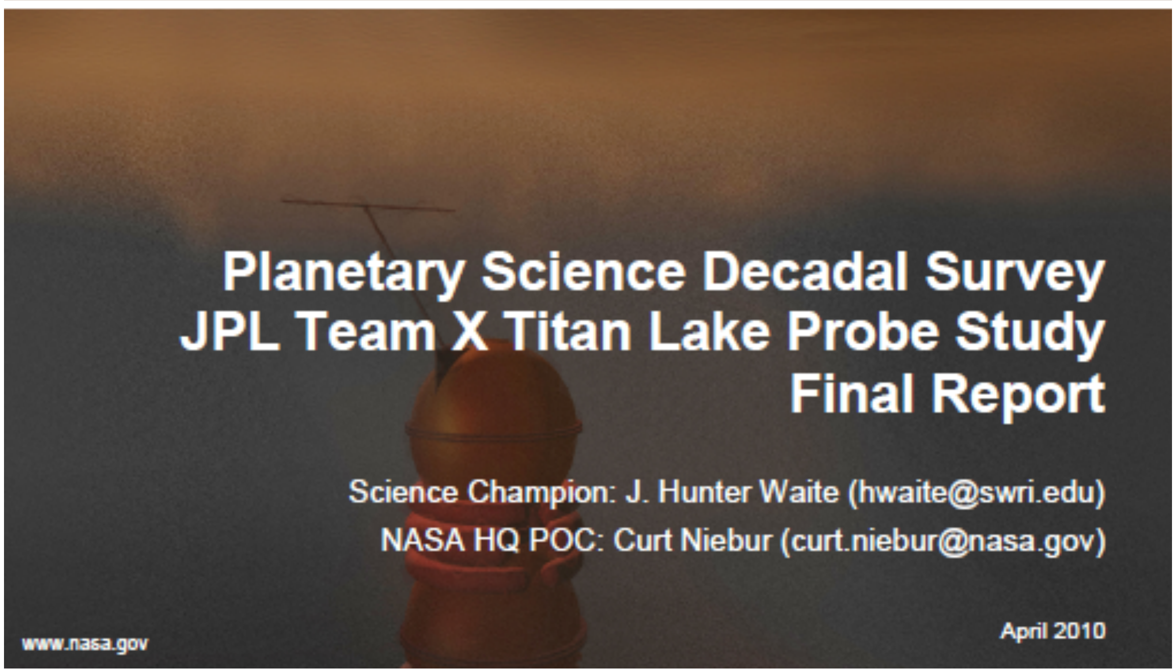



InterVideo WinDVD 5
InterVideo WinDVD 5
InterVideo WinDVD 5
InterVideo WinDVD 5



National Aeronautics and Space Administration

Mission Concept Study



Planetary Science Decadal Survey JPL Team X Titan Lake Probe Study Final Report

Science Champion: J. Hunter Waite (hwaite@swri.edu)
NASA HQ POC: Curt Niebur (curt.niebur@nasa.gov)

April 2010

www.nasa.gov

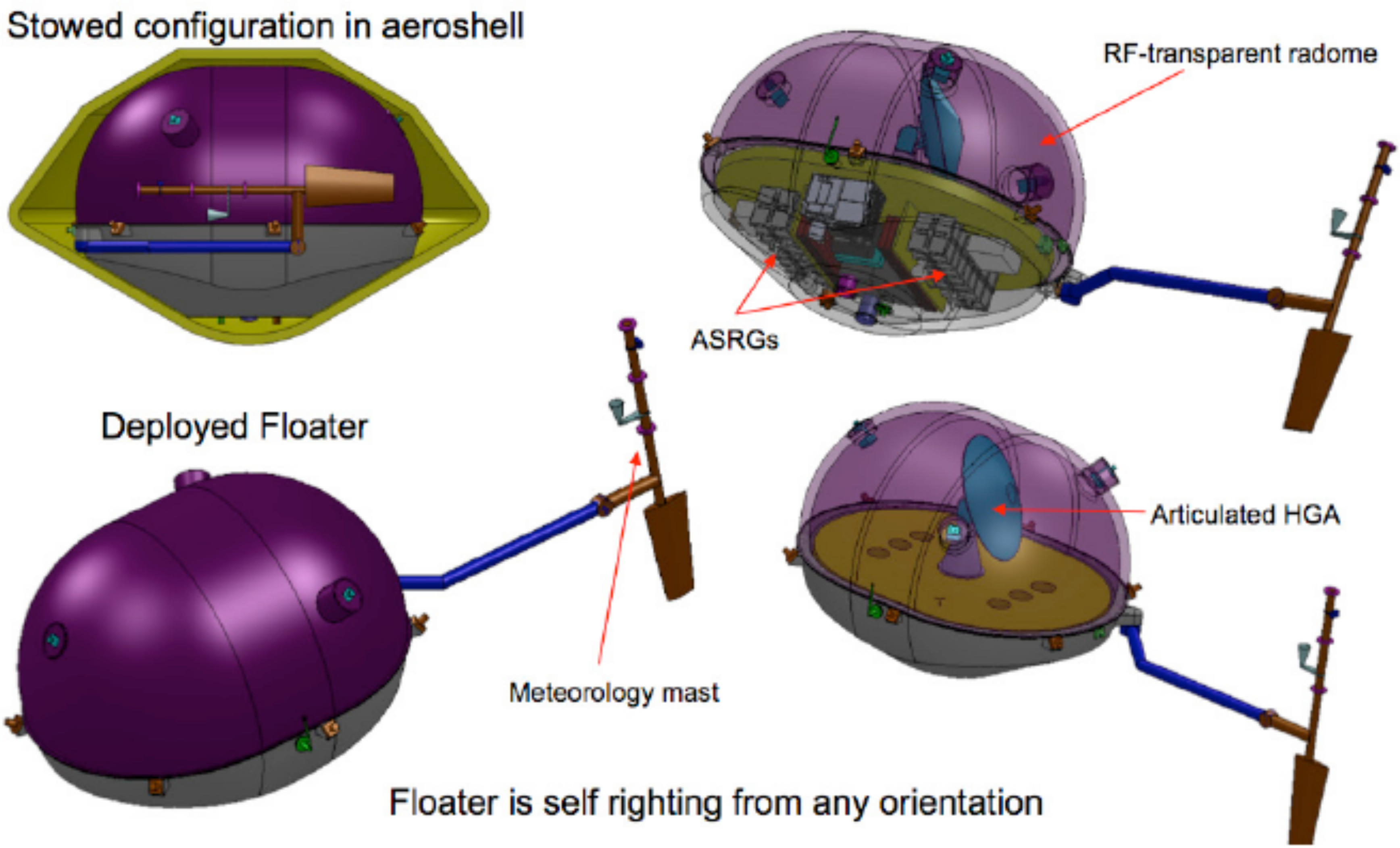
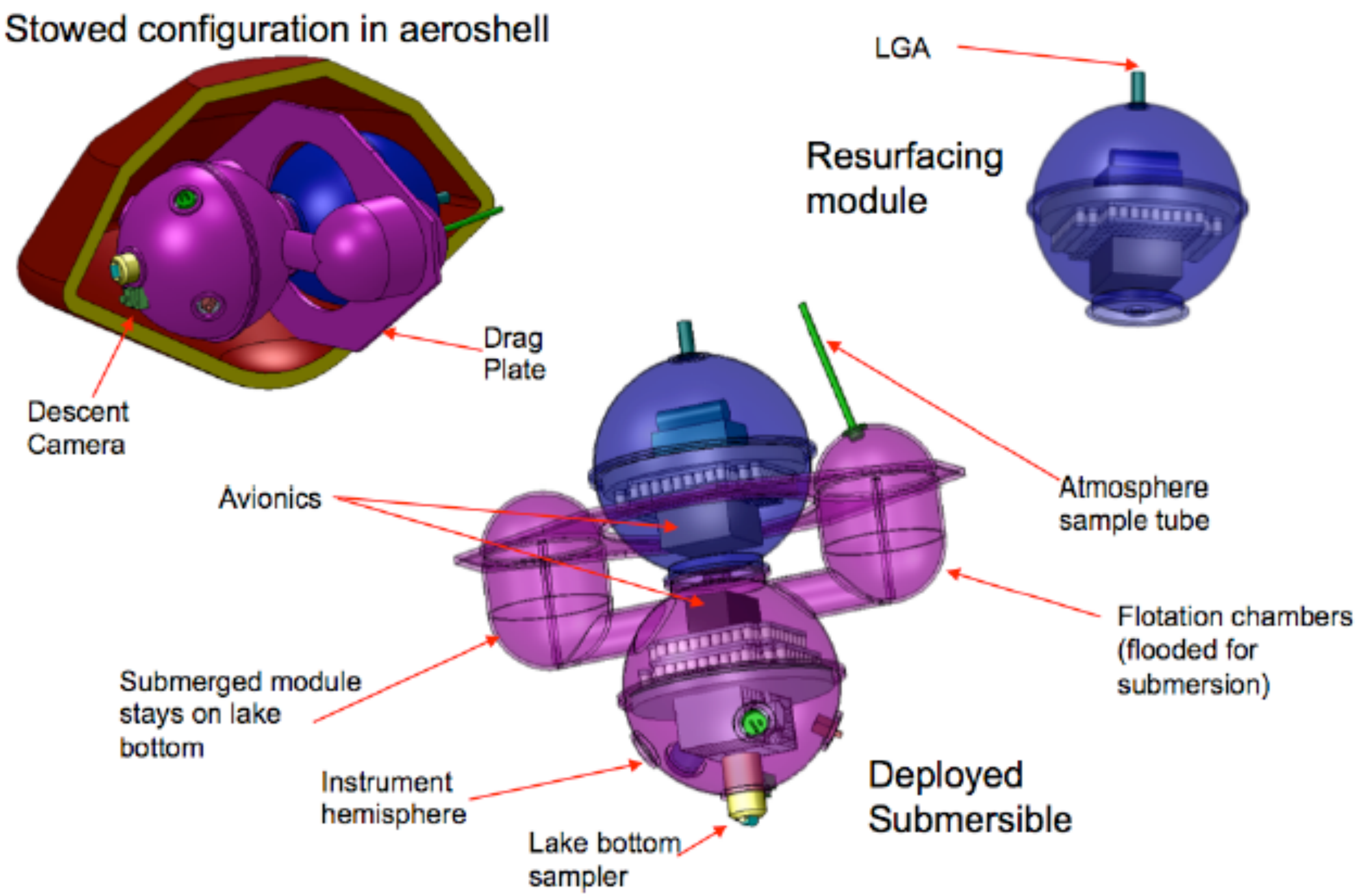


Figure 3-11. New Frontiers DTE Floating Lander Configuration


Stowed configuration in aeroshell
LGA
Resurfacing
module
Drag
Plate
Descent
Camera
Avionics
Atmosphere
sample tube
Flotation chambers
(flooded for
submersion)
Submerged module
stays on lake
bottom
Instrument
hemisphere
Lake bottom
sampler
Deployed
Submersible

TiME: Titan Mare Explorer
PI: Ellen Stofan

Mission & Science Team:

PI: Ellen Stofan, Proxemy
Project Mgmt: APL
S/C: LM
Ops: LM, JPL (nav)
Payload: APL, GSFC, MSSS
Deputy PI: J. Lunine, UA
Project Scientist: R. Lorenz, APL

Mission:

Lander msn to Titan's *Ligeia Mare* methane-ethane polar sea, 96 days on surface

Goals:

- Understand Titan's methane cycle through study of a Titan sea.
- Investigate Titan's history & explore the limits of life

Instruments:

- Meteorology & physical properties (MP3)
- Mass Spec for Lake Chemistry (NMS),
- Descent and Surface Imaging Cameras

Efficient Trajectory:

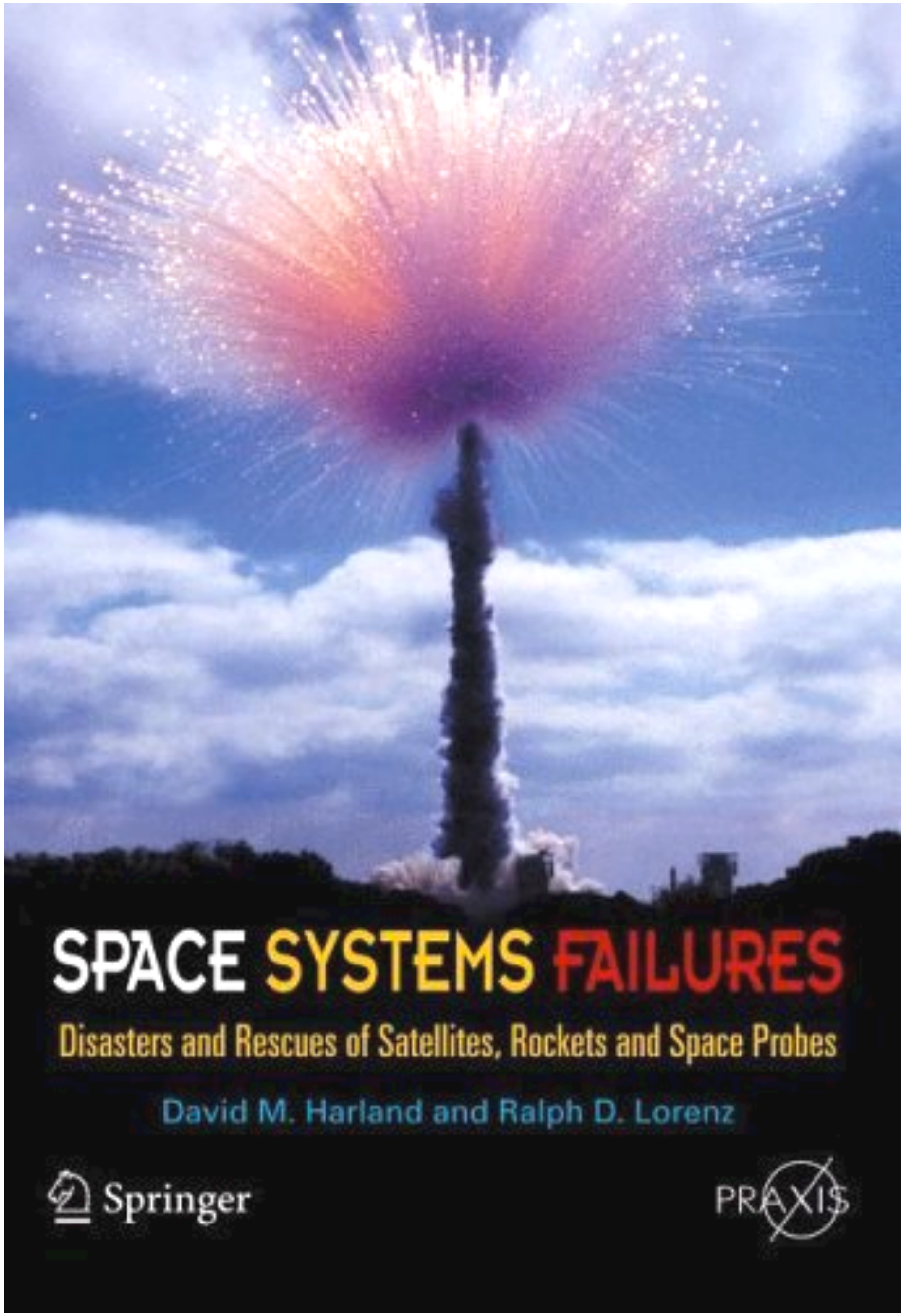
- Launch 2016
- Cruise 7.5 years (EGA, JGA)
- Entry 2023

Mission Features:

- Focused science objectives
- High-heritage instruments
- Simple cruise, no flyby science
- Simple surface operations
- ASRGs, launch vehicle are GFE

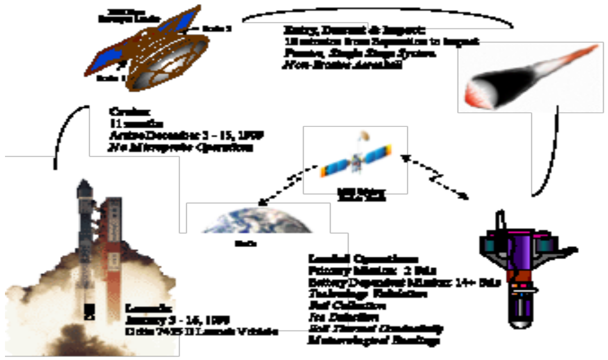
TiME Phase A announcement has even stimulated the public to start imagining the mission.

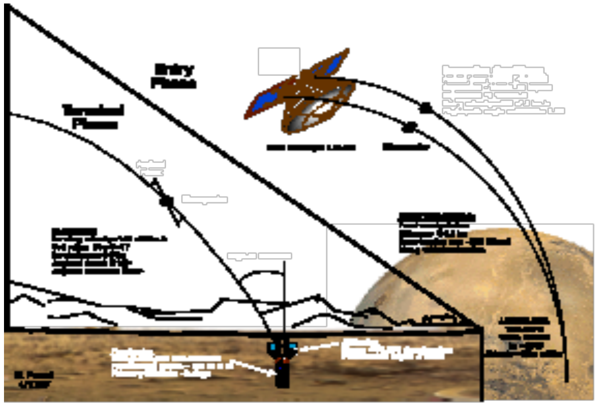
This impression by Simon Stålenhag, a video game concept artist in Sweden


SPACE SYSTEMS FAILURES
Disasters and Rescues of Satellites, Rockets and Space Probes
David M. Harland and Ralph D. Lorenz
Springer
PRAXIS

DS-2

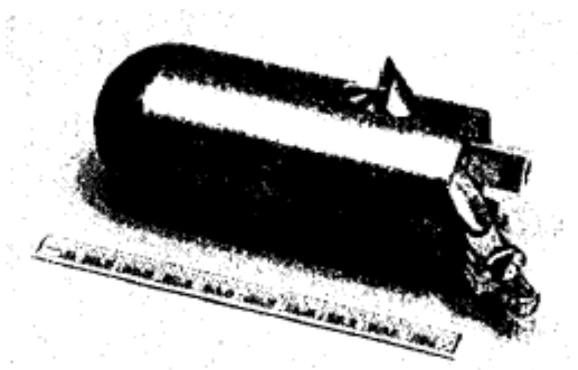
MARS MICROPROBE MISSION PROFILE

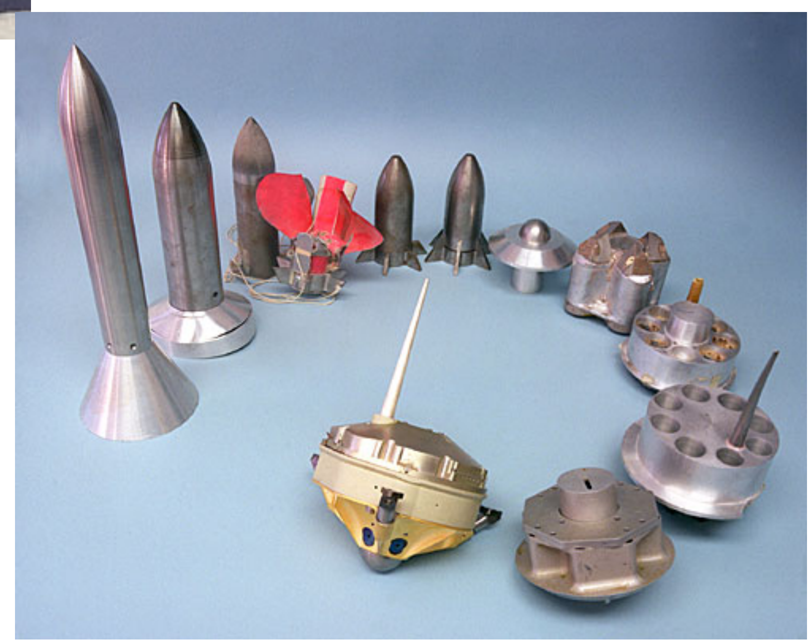


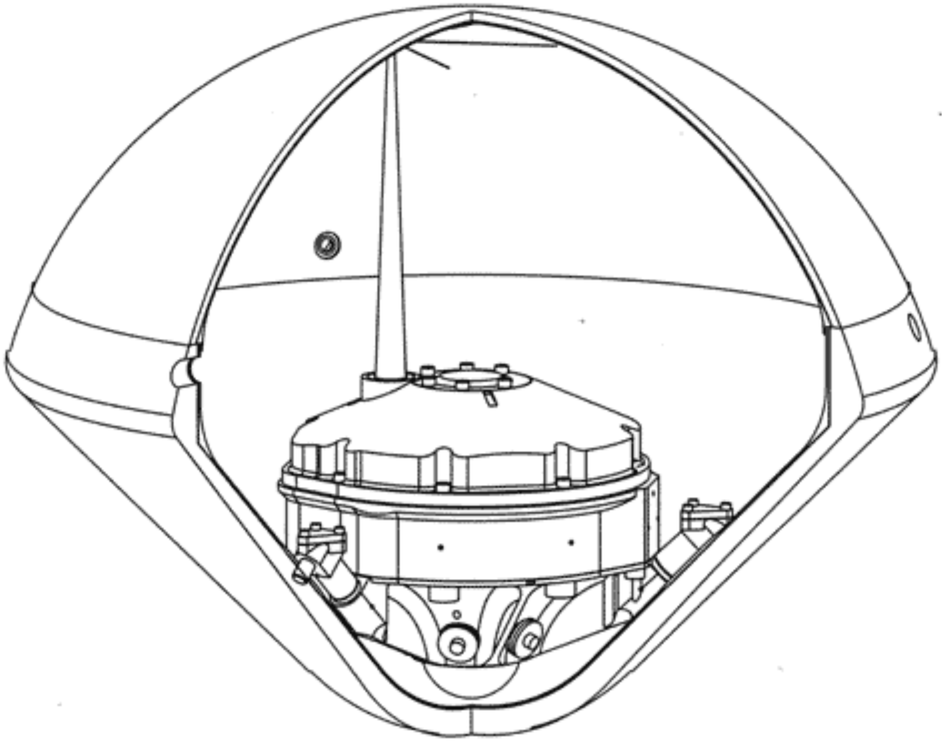


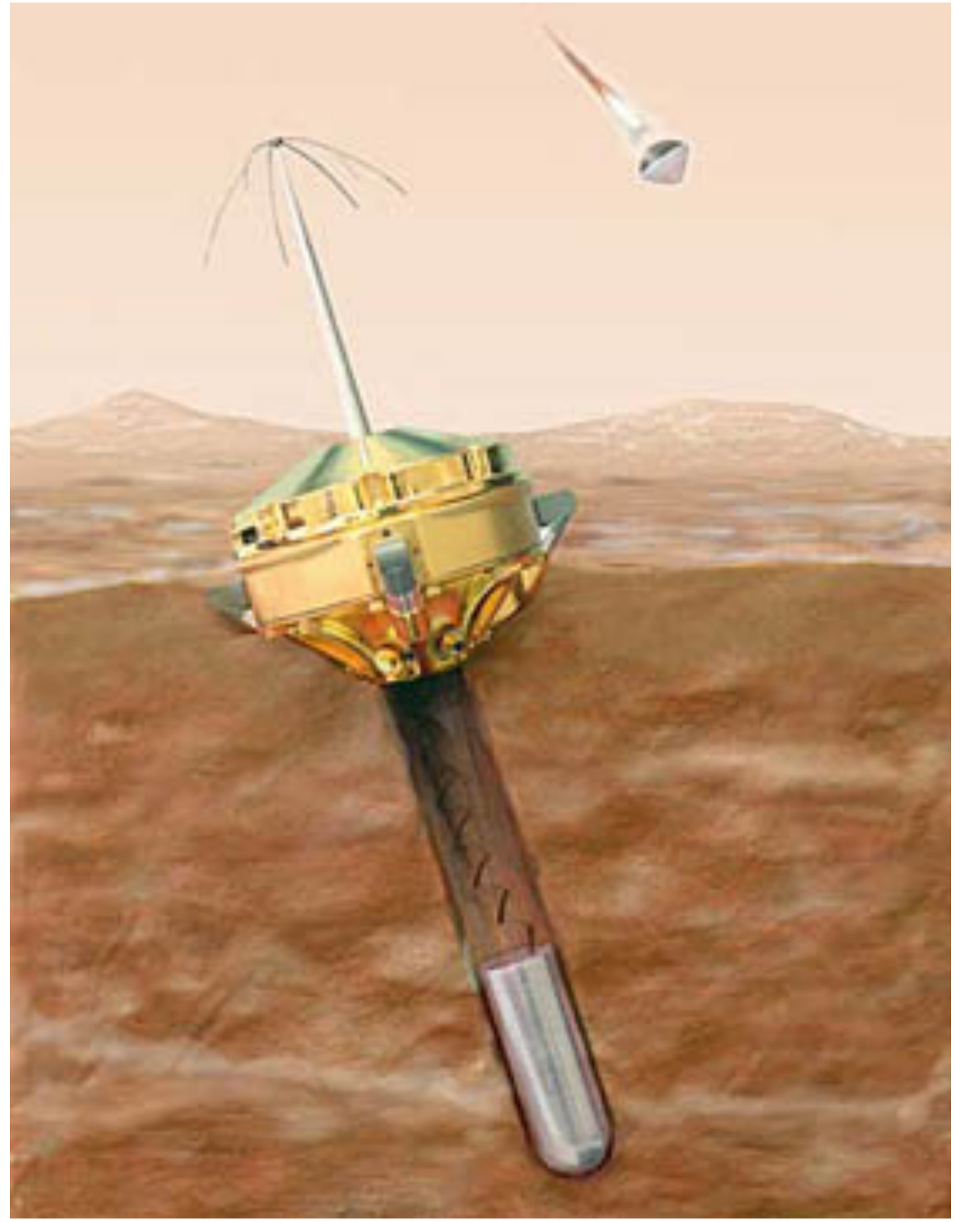
Entry
Phase
Terminal
Phase

Early concept testing 1995-1996. Eliminated 'digestive tract' and 'side-scoop' as nonviable mear acquiring regolith sample



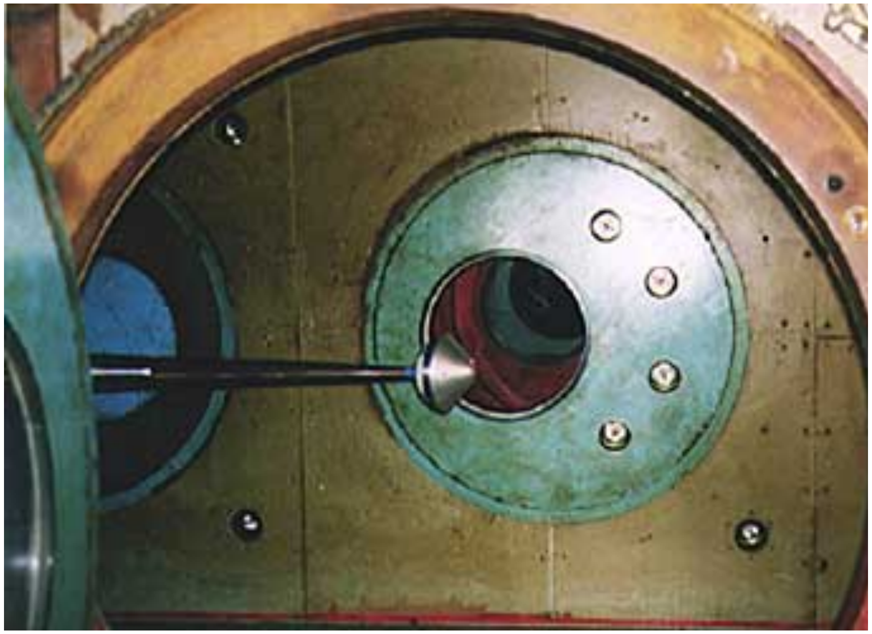




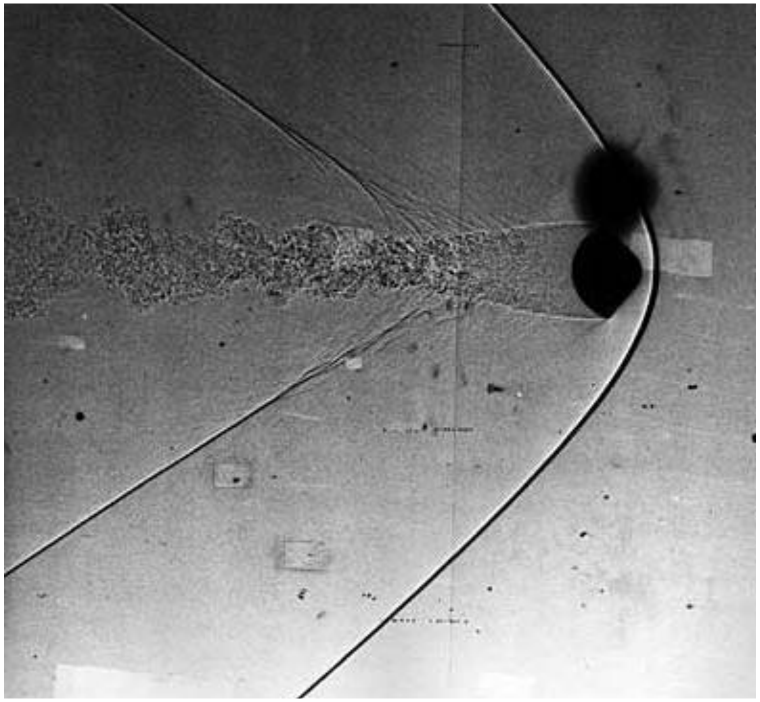


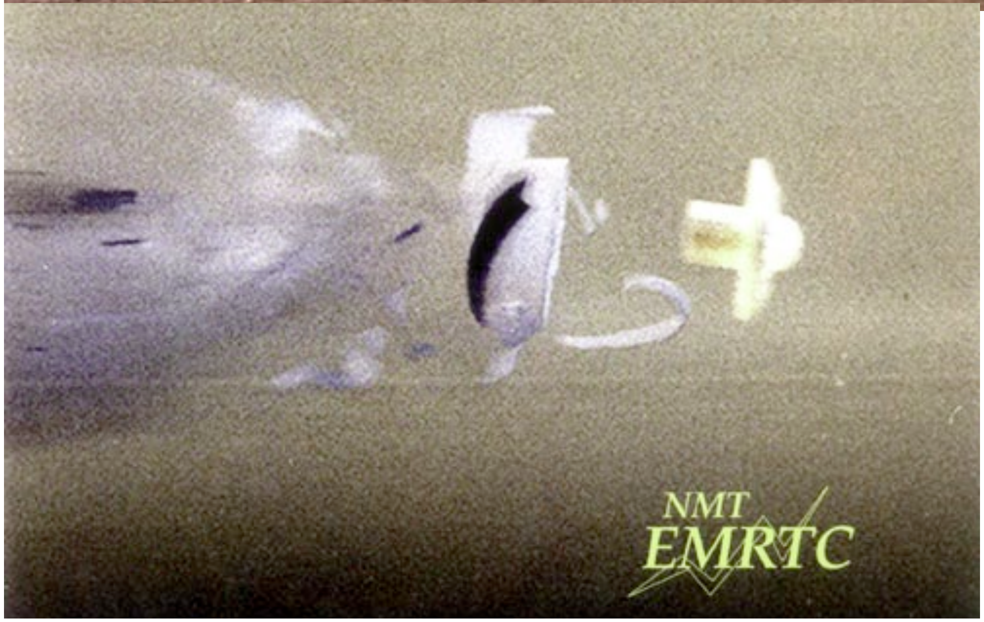
Frangible entry shell 35cm diameter, 28cm high (1.2kg PICA/SIRCA aeroshell)
40mm wide forebody - 0.67kg
1.7kg Aftbody contains batteries, telecom.

Passive entry stability drives squat configuration - including 'ballast' - tungsten nose on forebody to bring cg forward)

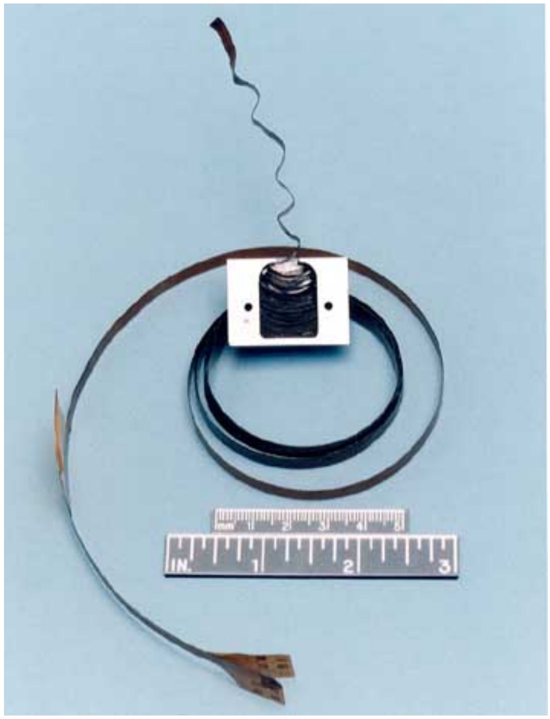


Aeroballistic testing at Eglin AFB, Fl and Wind Tunnel tests at TsNIIMash, Russia





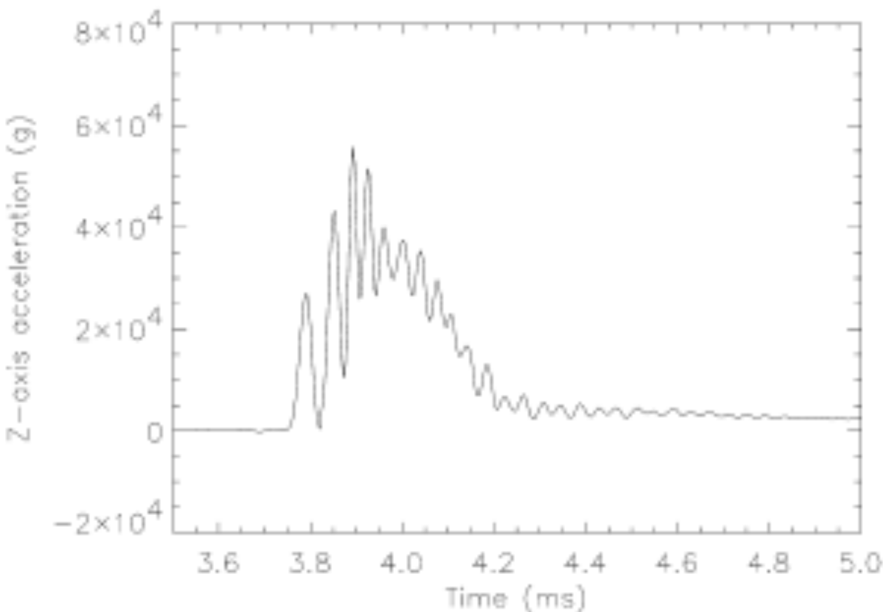
Impact testing in New Mexico 200m/s.
~60 development shots
~6 instrumented science shots



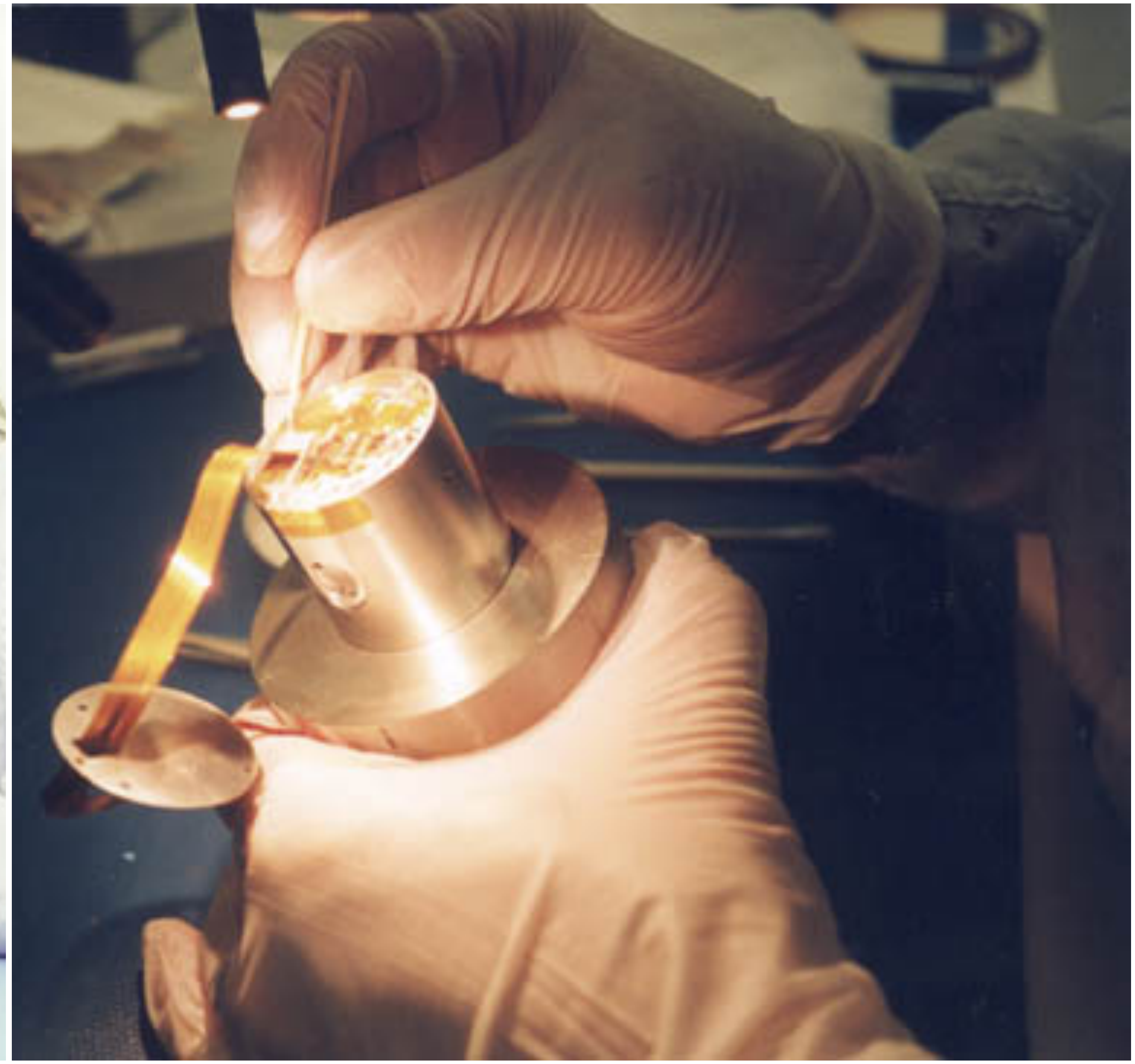
Flexible interconnect between fore- and aft-body.

Separation at impact made penetration depth prediction rather complicated.

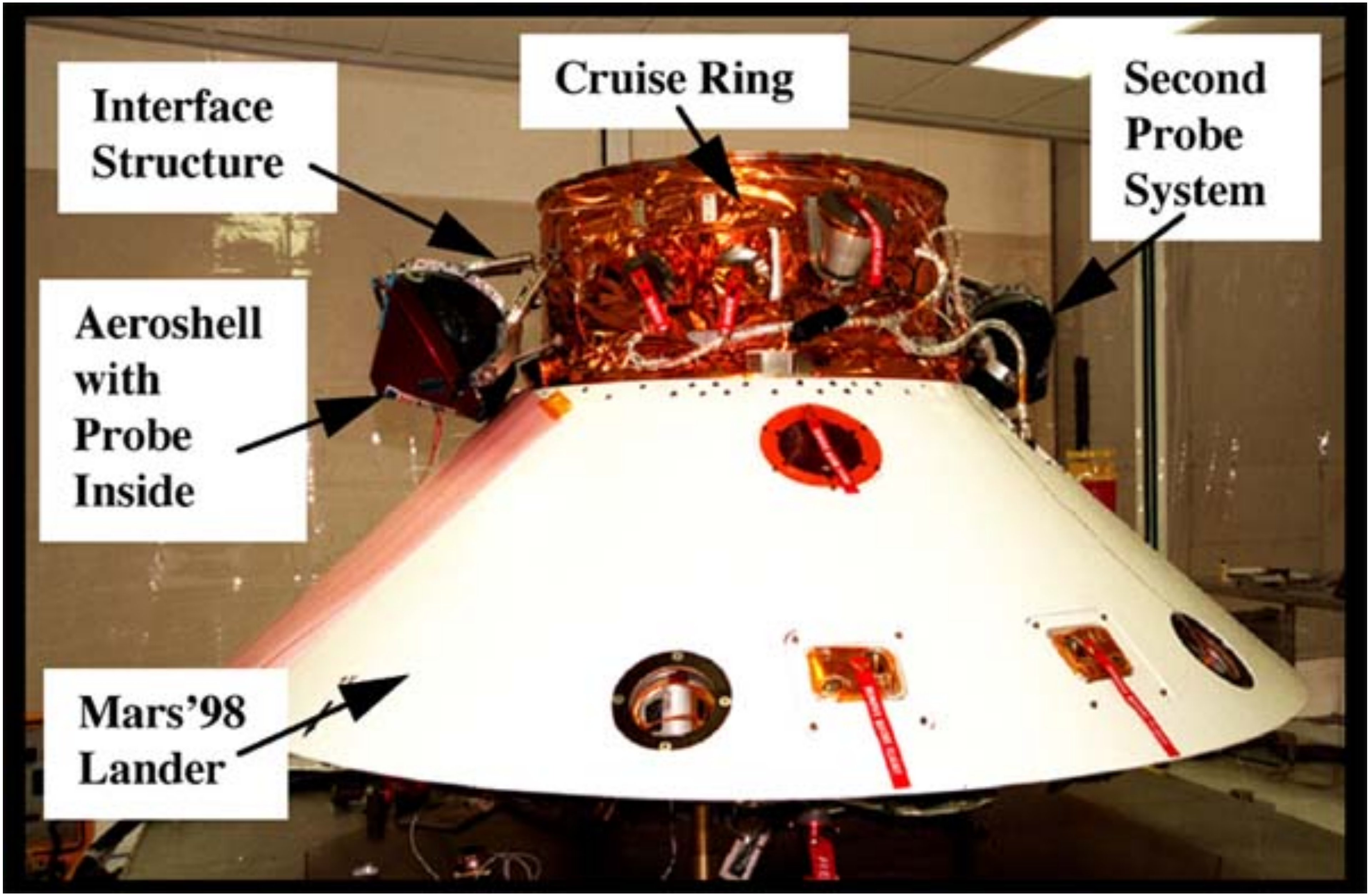
Accelerometer record provided reasonable estimate of penetration depth



New insights into e.g. thermal and triboelectric effects of impact.

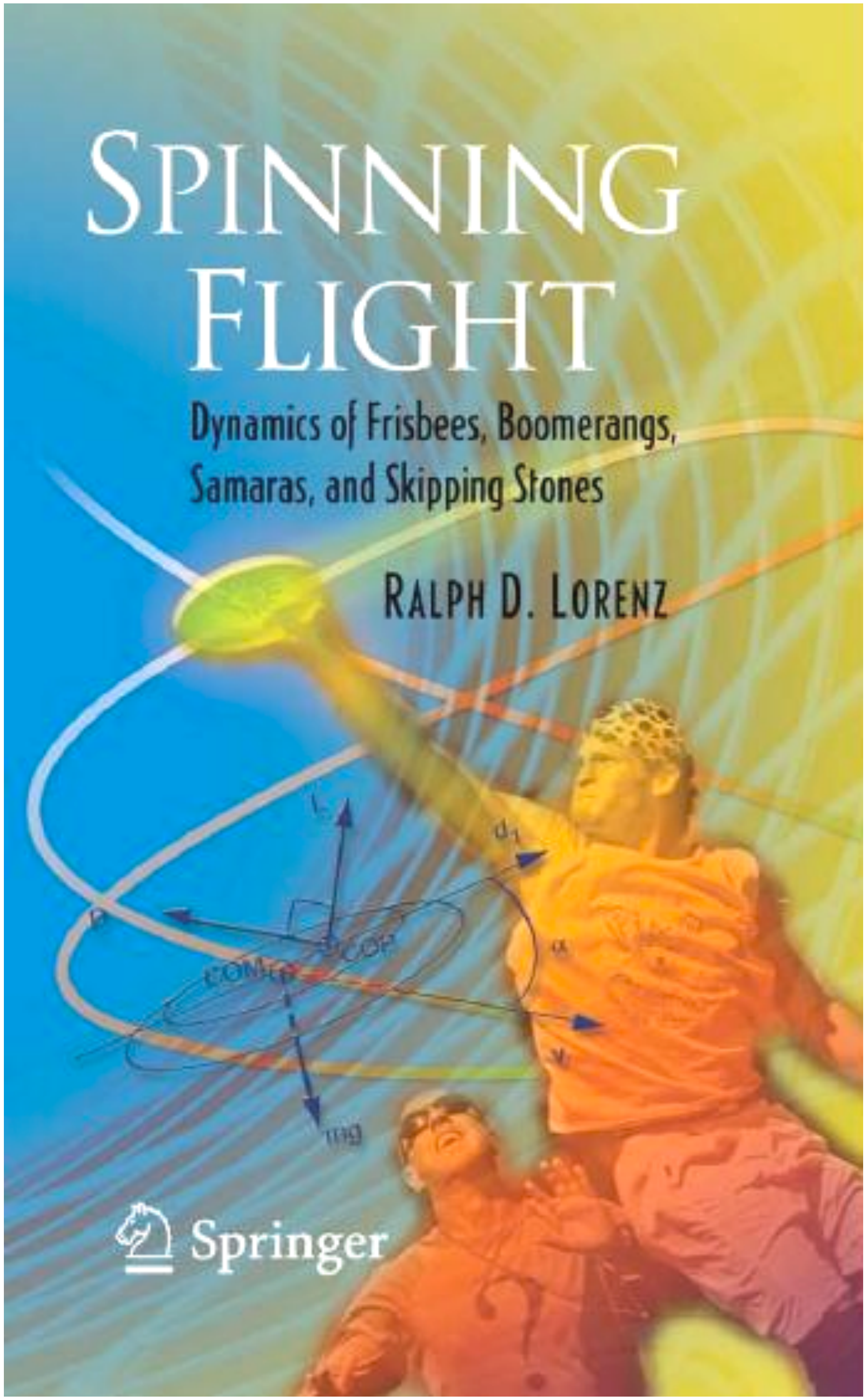


A particular challenge with very small tightly-integrated systems - insufficient volume for fasteners and access - press-fit or adhesive attachment makes it impossible to non-destructively disassemble after assembly….


Interface Structure
Cruise Ring
Second Probe System
Aeroshell with Probe Inside
Mars'98 Lander

Launch 3.21pm 3rd January 1999 on Delta II

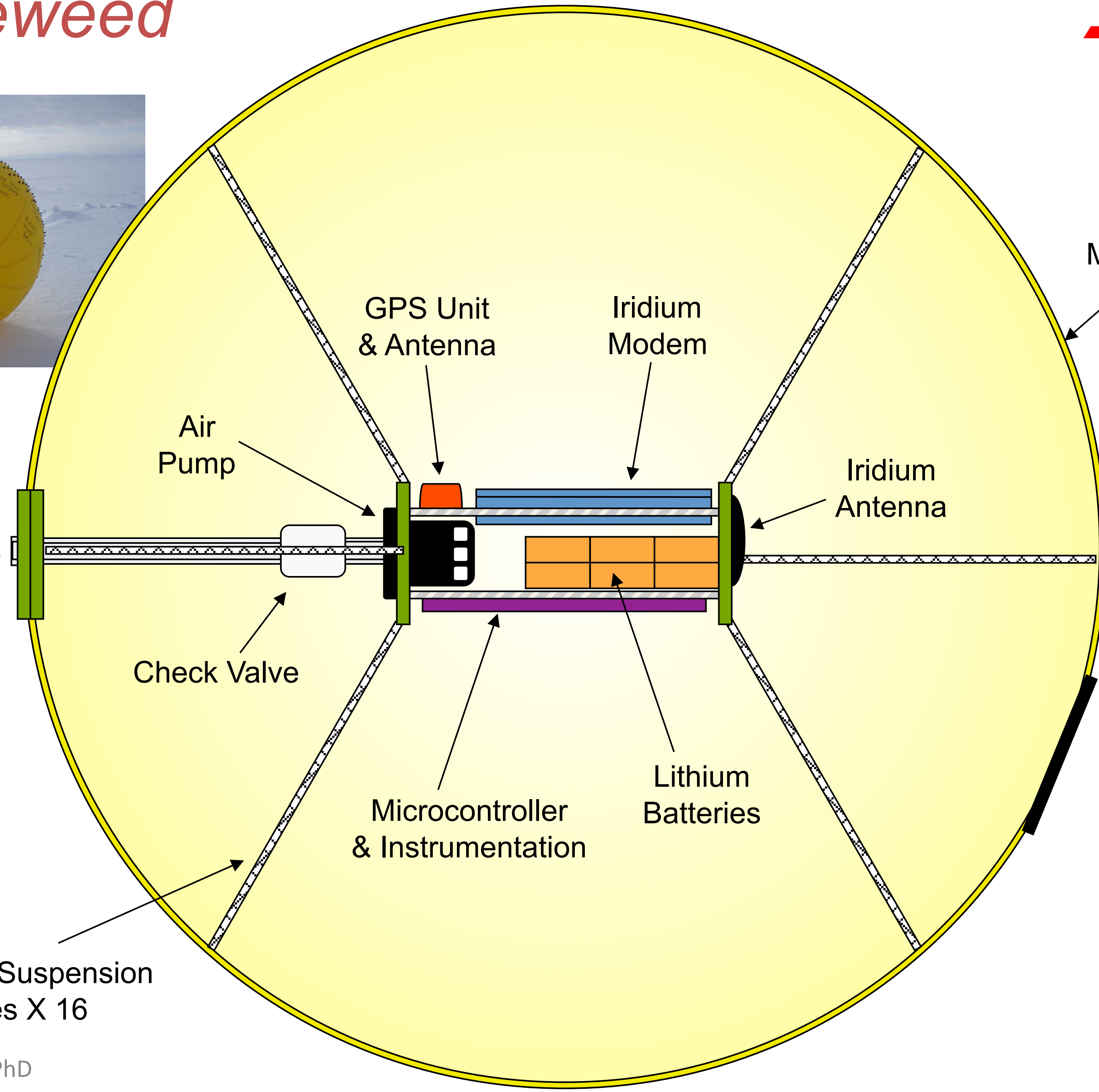
Tumbleweeds and
Samaras



Tumbleweed (aka Russian Thistle, Salsola Pestifera) uses ambient wind energy for locomotion.   Has been considered an inspiration for Mars vehicle.

Tumbleweed

Polar Rover



Alberto Behar, PhD

Not to scale

Field trials at Willcox Playa, Arizona

(reported in Lorenz et al., IPPW4, 2006)

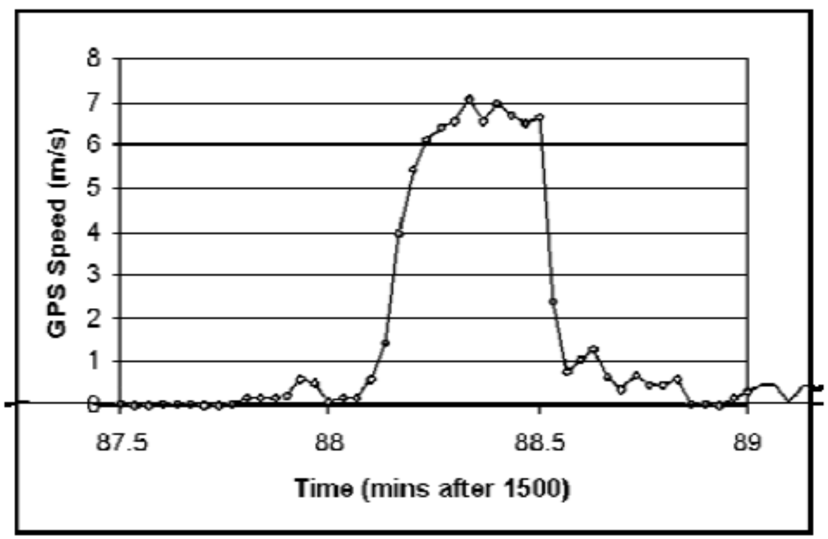
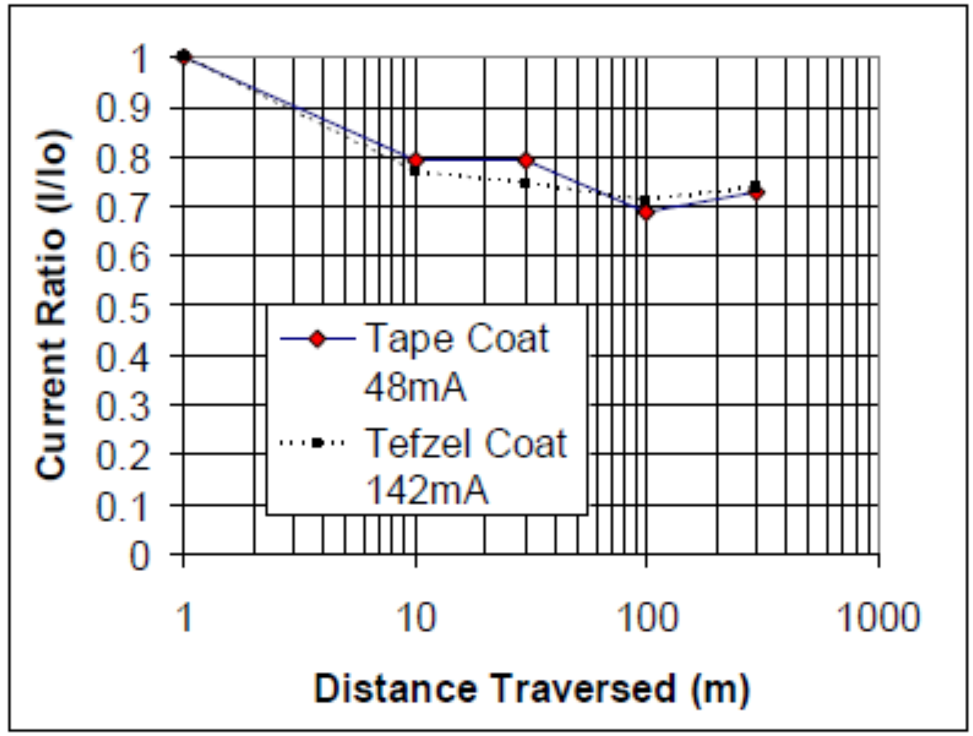
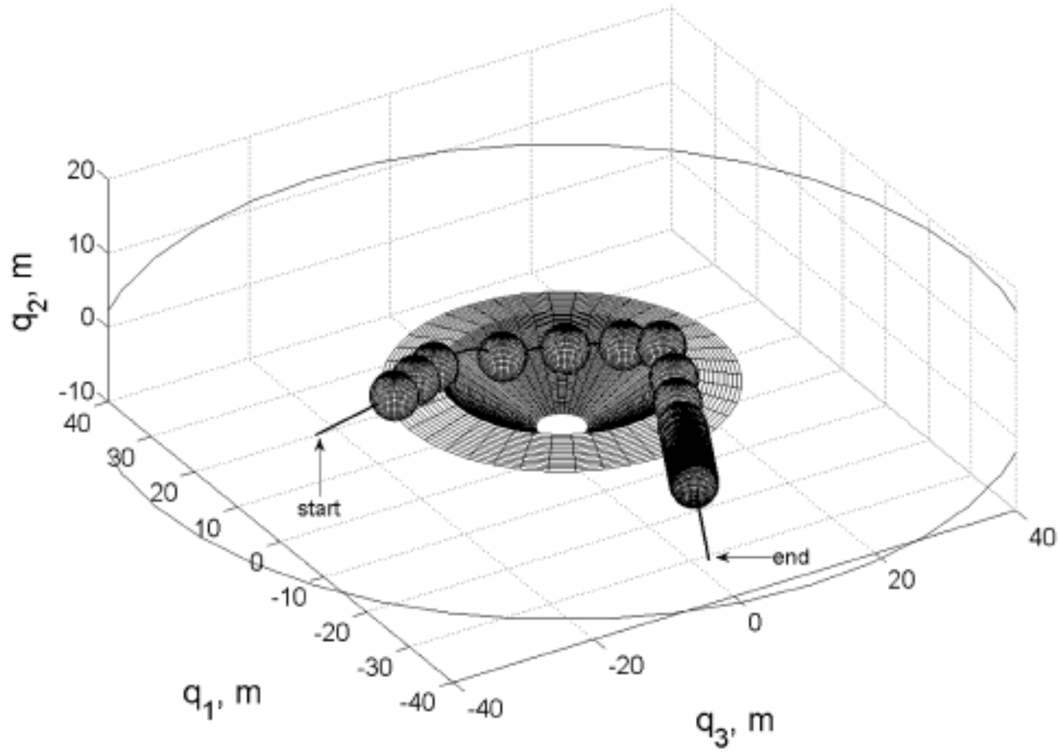


Figure 13. Tefzel-coated solar cell at start (above) and after 300m of rolling (below).



Flexible solar cells may be viable power source : dust deposition appears to be self-limiting, allowing 70% of clean solar array current.

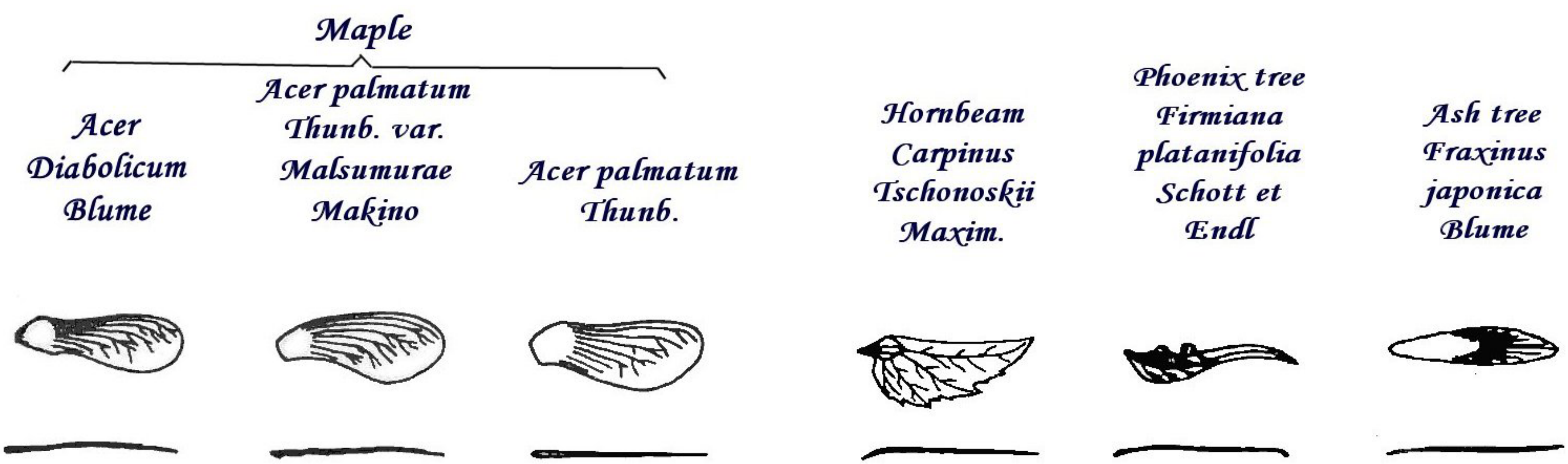


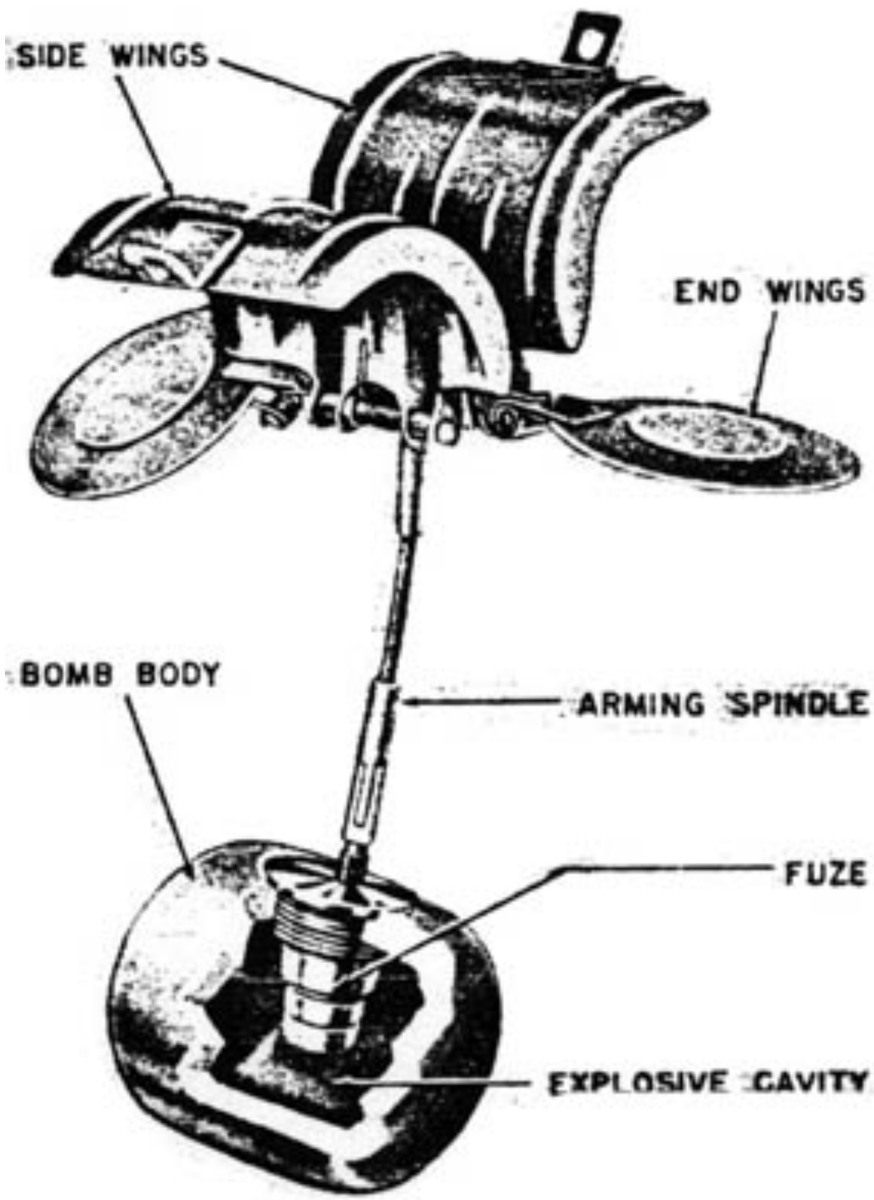
Simulations of bouncing/rolling/skidding dynamics are reaching a high level of fidelity (Hartl and Mazzoleni).

Delivery / deployment could use serious study.   Deploy in space with Low-β entry ?

What are the science questions addressable by undirected mobility of uncertain duration ?

Autorotating Seed-Wings (‘samaras’)

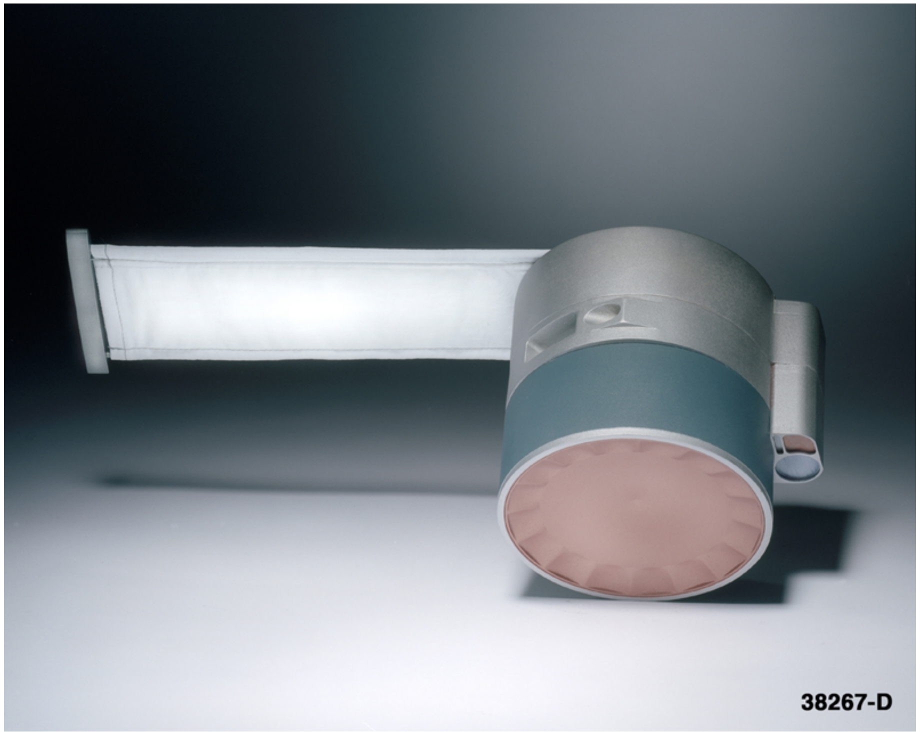


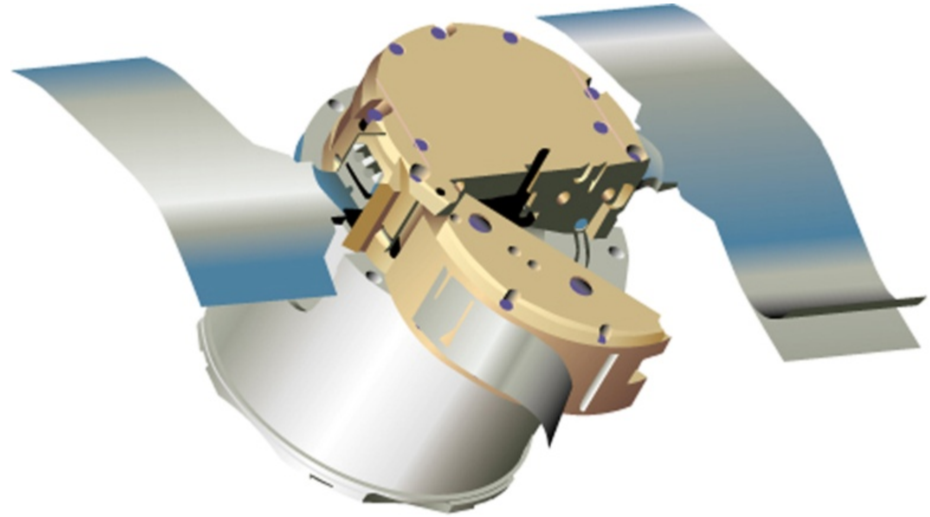


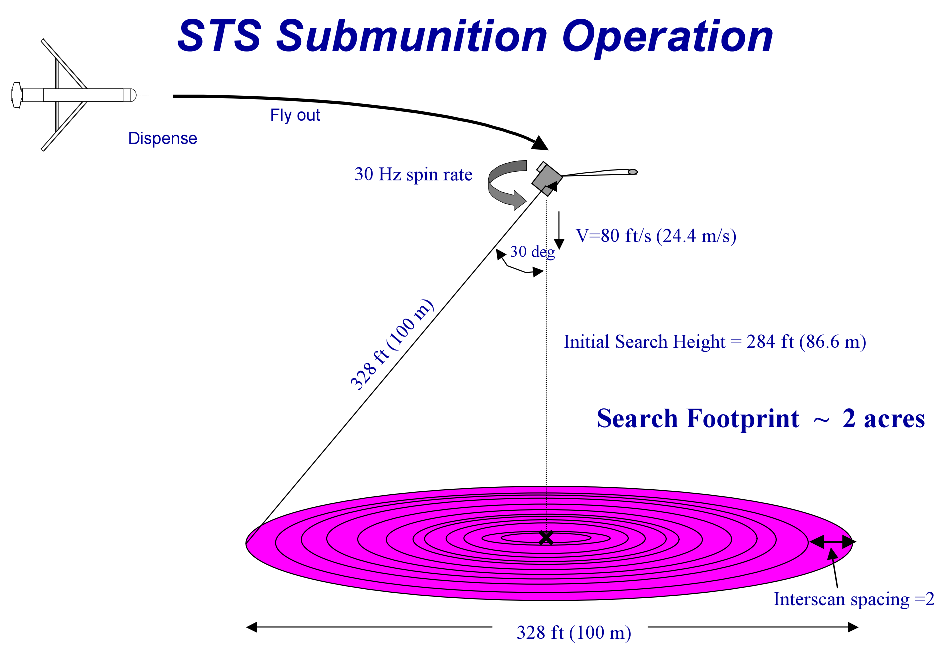
WWII German 'Butterfly Bomb' - an early cluster munition, used against British towns, and in North African and Russian fronts.

Autorotation armed the charge.

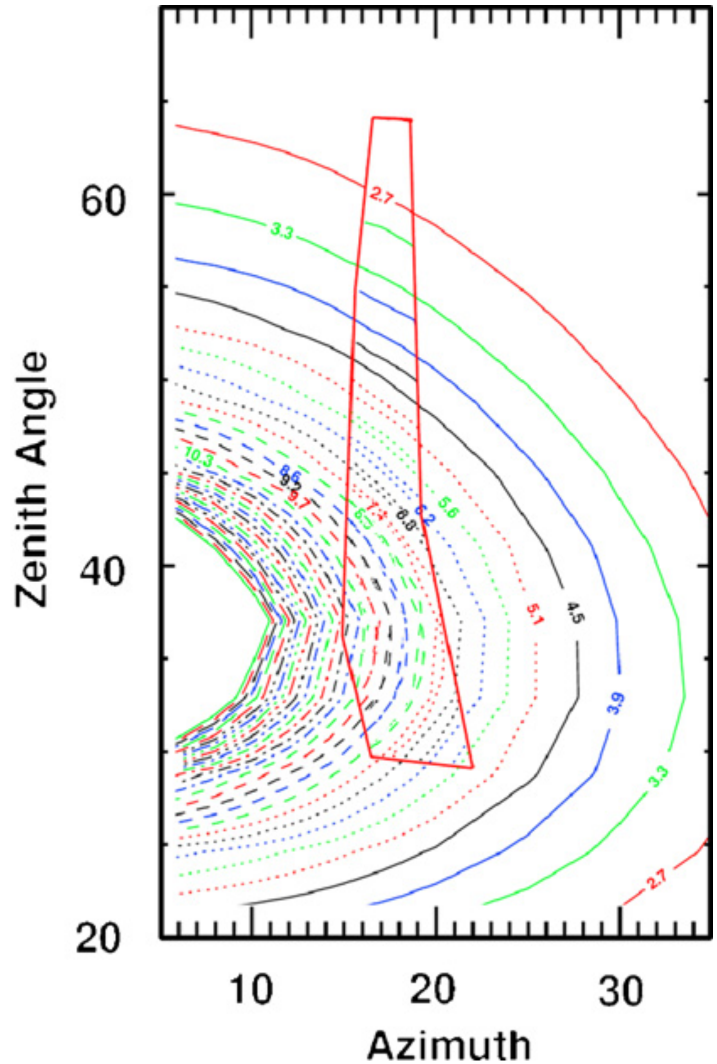
Copied by US in Korea and Vietnam

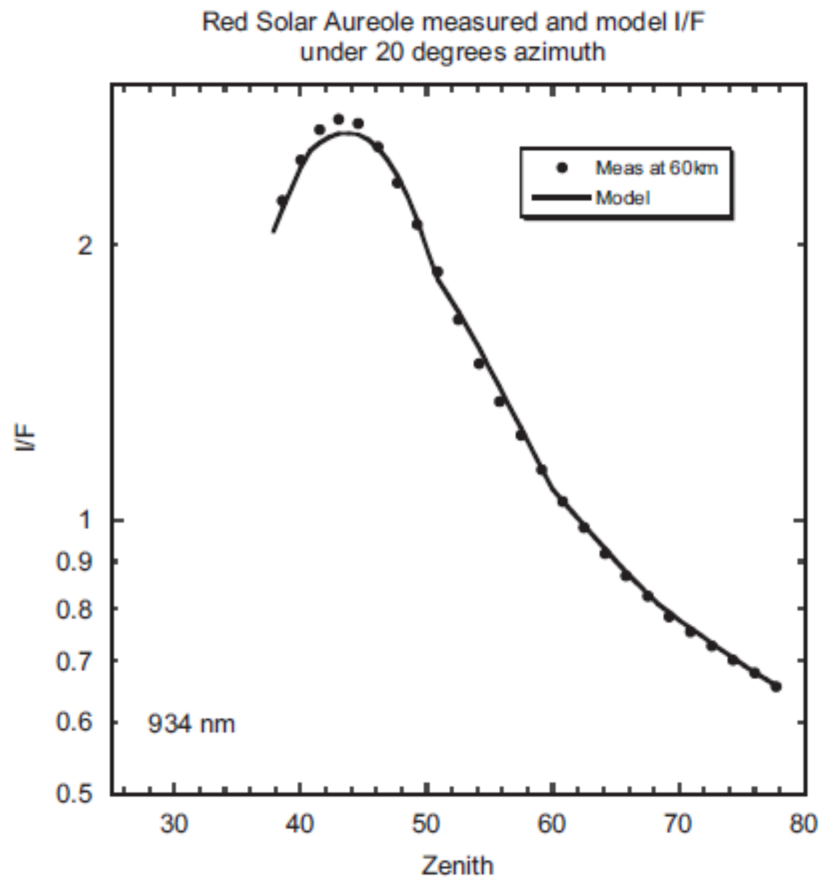






Modern samara-wing munitions are smarter. Use directional self-forging projectile to blast down onto thin upper skin of armored vehicles, triggered by boresighted microwave radiometer. Autorotation scans boresight around in a shrinking circular footprint.





Autorotating samara well-suited to atmospheric scattering measurements (Titan, Saturn etc.…)

Mars application – packaging for network mission? Flexible solar panel acts as wing ?

PROGRAM
FORUM ON INNOVATIVE APPROACHES TO
OUTER PLANETARY EXPLORATION
2001–2020
February 21–22, 2001 Lunar and Planetary Institute, Houston, Texas

Jensen J. R. * Raney R. K.
Delay/Doppler Radar Altimetry for Outer Planet Applications

Beauchamp P. * Beauchamp J. Dougherty D. Raulin F. Smith M. Welch C.
Shapiro R. Lunine J.
Approaches for Exploring the Organic Evolution of Titan's Surface

Sittler Jr. E. C. * Acuna M. Burchell M. J. Coates A. Farrell W. Flasar M.
Goldstein B. E. Gorevan S. Hartle R. E. Johnson W. T. K. Kojiro D. R. Niemann H.
Nilsen E. N. Nuth J. Smith D. Zarnecki J. C.
Titan Orbiter Aerorover Mission

Jones J. A. *
Inflatable Vehicles for In-Situ Exploration of Titan, Triton, Uranus, Neptune

Kerzhanovich V. * Yavrouian A. Cutts J. Colozza A. Fairbrother D.
Titan Airship Surveyor

Lorenz R. D. *
Flexibility for Titan Exploration: The Titan Helicopter

Young L. A. *
Exploration of Titan Using Vertical Lift Aerial Vehicles

Bartlett P. W.* Rafeek S. * Kong K. Y. Gorevan S. P. Ummy M. A.
A Balloon-delivered Subsurface Sample Acquisition and Transfer Mechanism
AND
Touch and Go Surface Sampler (TGSS)

Thick atmosphere - good for lighter-than-air and heavier-than-air

Low Titan gravity helps heavier-than-air flight

Rotary-wing concepts attractive for surface access.

Actuator disk theory - hover power for fixed mass, rotor is 38x less than on Earth

Lorenz (2000) advocated helicopter with battery trickle-charged by RTG. Fly for 6 hours (~200km) then land, conduct surface science and recharge for Titan night

But introduces tyranny of choice…..

(artist's impression by James Garry)

EXPLORATION OF TITAN USING VERTICAL LIFT AERIAL VECHICLES. L.A. Young, Army/NASA Rotorcraft Division, M/S T12-B, Ames Research Center, Moffett Field, CA 94035 (layoung@mail.arc.nasa.gov).

Introduction: Autonomous vertical lift aerial vehicles (such as rotorcraft or powered-lift vehicles) hold considerable potential for supporting planetary science and exploration missions. Vertical lift aerial vehicles would have the following advantages/attributes for planetary exploration: low-speed and low-altitude detailed aerial surveys; remote-site sample return to lander platforms; precision placement of scientific probes; soft landing capability for vehicle reuse (multiple flights) and remote-site monitoring; greater range, speed, and access to hazardous terrain than a surface rover; greater resolution of surface details than an orbiter or balloons. Exploration of Titan presents an excellent opportunity for the development and usage of such vehicles.

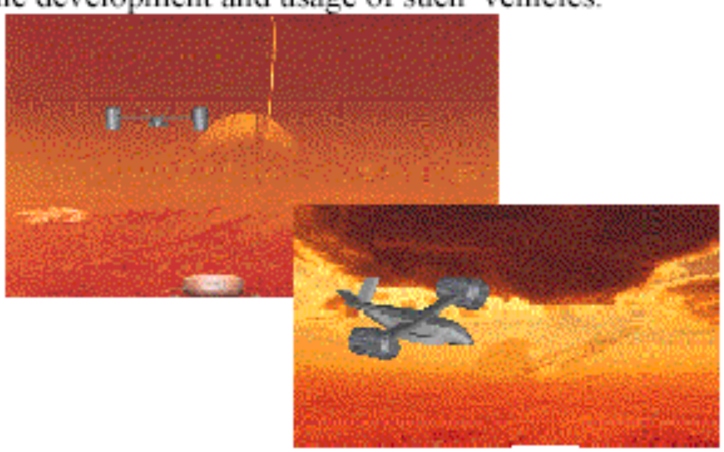


Fig.1-Titan Vertical Lift Aerial Vehicle

Figure 2 shows estimates of hover total shaft power for a notional Titan tilt-nacelle VTOL vehicle having two ducted fans that can pivot at the wing tips. A Titan VTOL's ducted fans will be very small and consume very little power as a result of the high atmospheric density near Titan's surface and it's low gravity field.

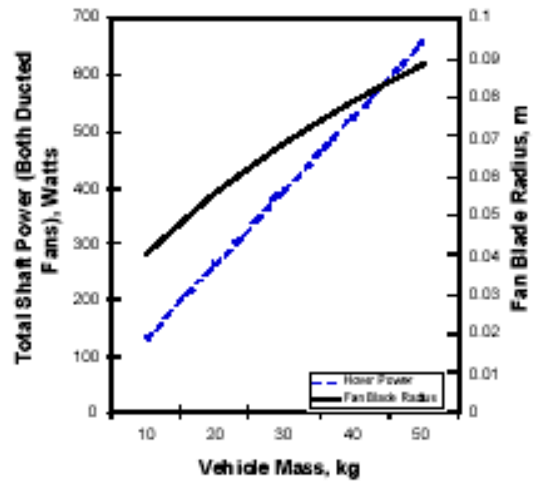
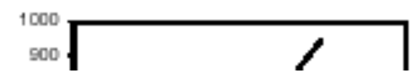


Fig.2-Ducted Fan Hover Performance

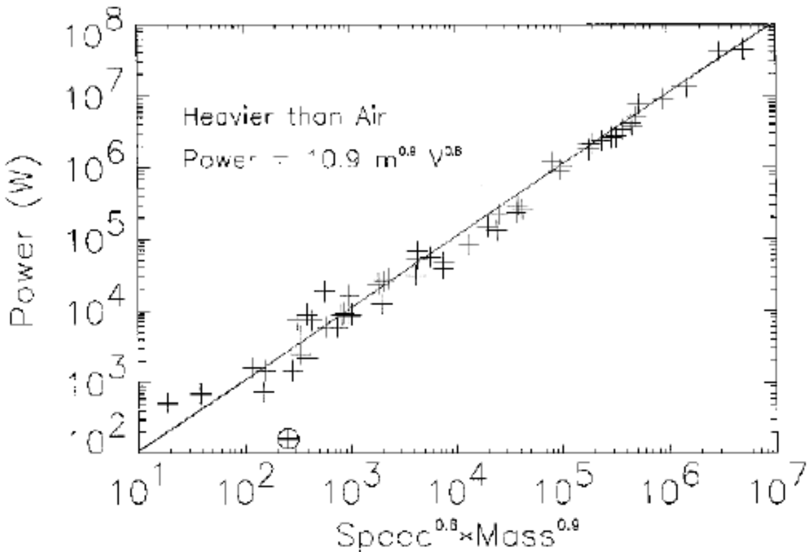
Figure 3 shows range estimates for a 50kg Titan twin tilt-nacelle/ducted-fan VTOL vehicle, assuming power matching between the hover and cruise design points.

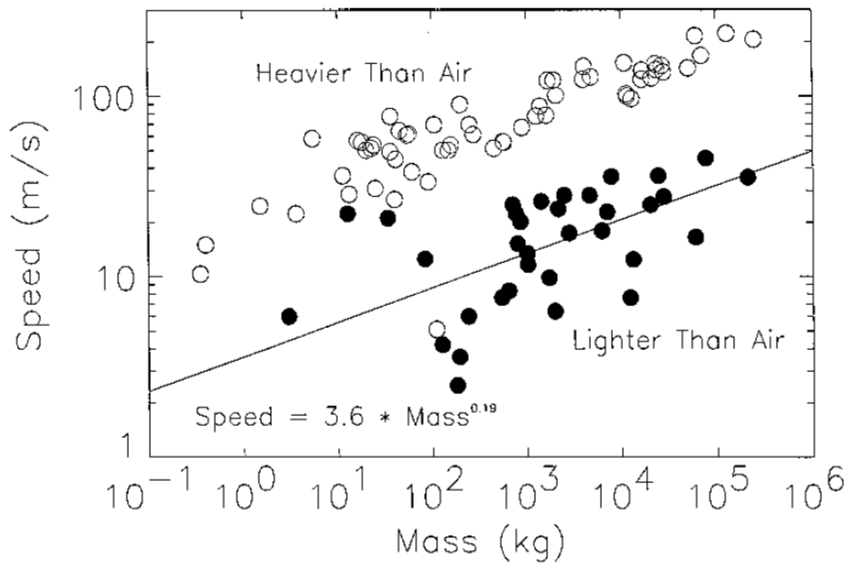


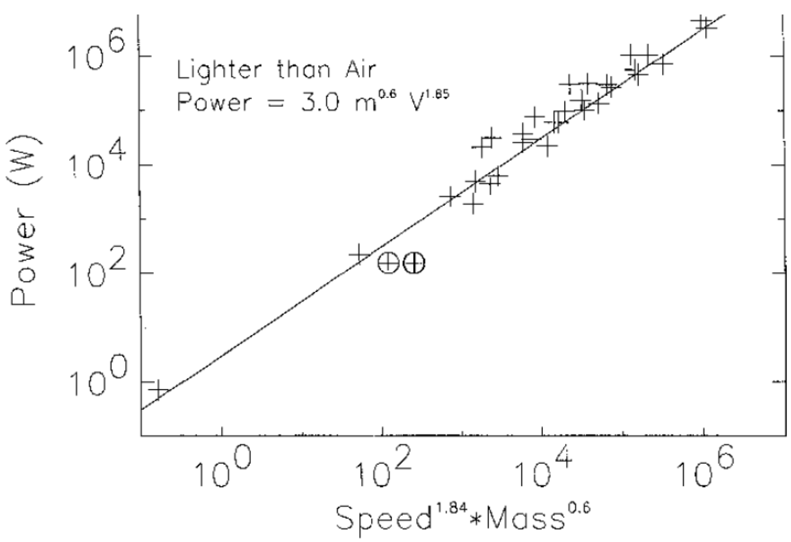
JOURNAL OF AIRCRAFT
Vol. 38, No. 2, March–April 2001

Ralph D. Lorenz*

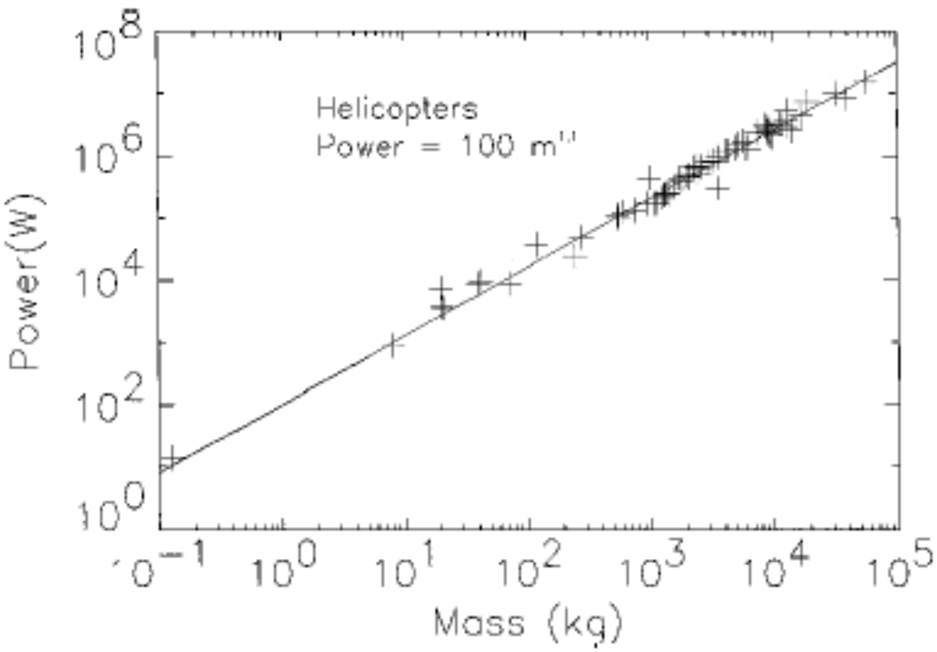
Flight Power Scaling of Airplanes, Airships, and Helicopters: Application to Planetary Exploration

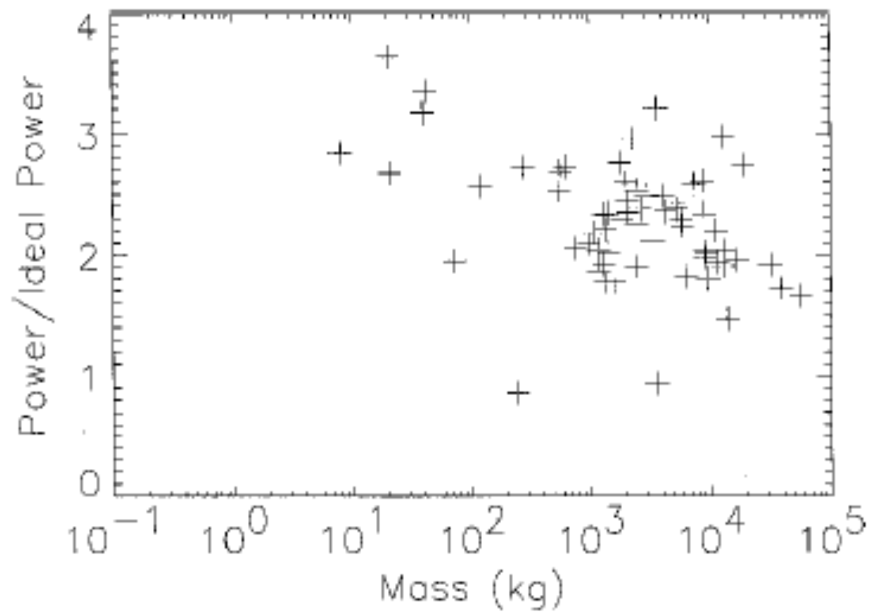


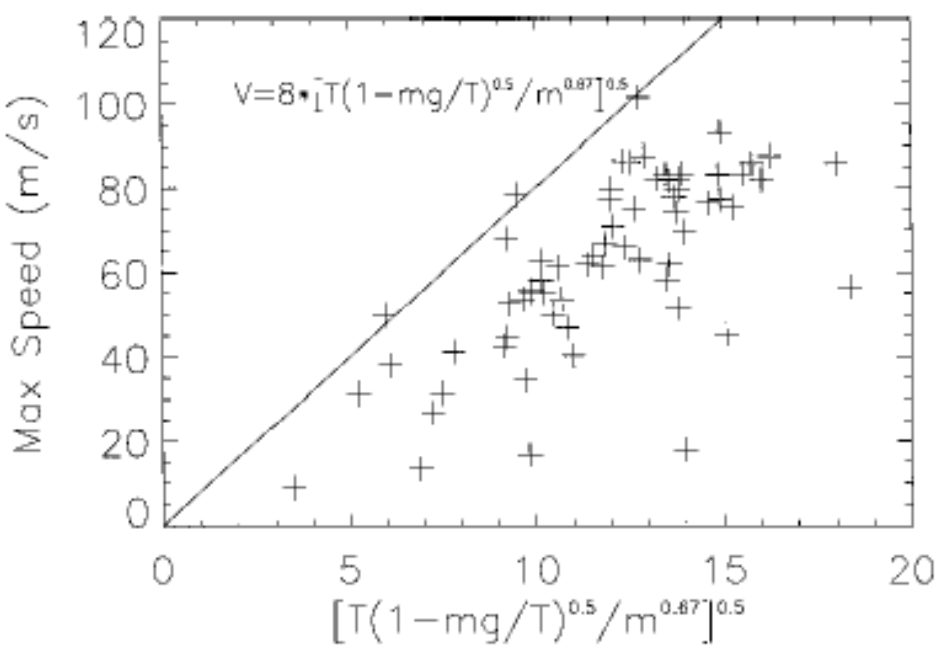




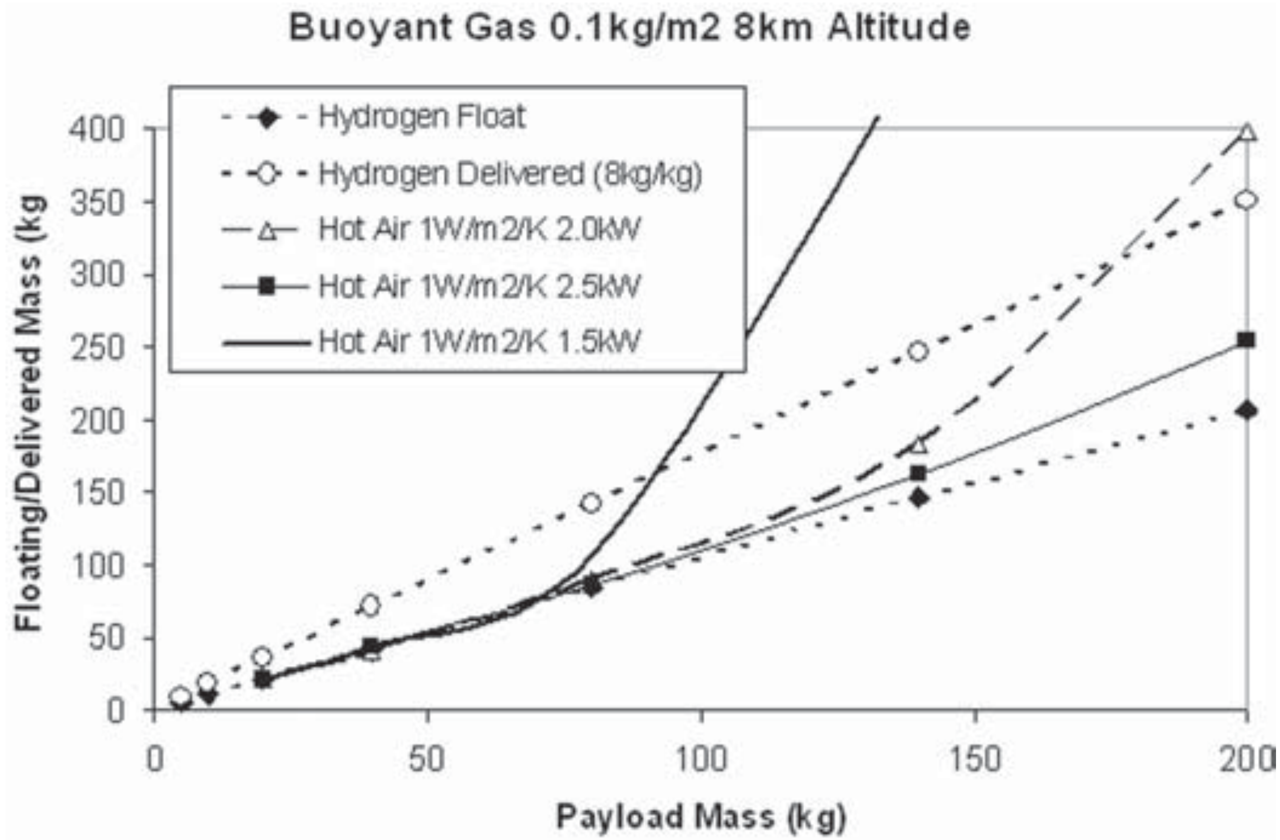
Intuitively we associated airships with large, slow vehicles. Indeed, installed power seems to vary as ~m^0.8V^0.9 for aircraft, and ~m^0.6V^1.85 for airships. These deviate from simple expectations (e.g. V^3 for aircraft) because larger vehicles tend to be faster, and have larger propellers.







A good starting point for scaling rotorcraft is the hover power, calculated using actuator disk theory (power required is proportional to weight^1.5, and inversely proportional to rotor diameter). In practice, more massive vehicles have bigger rotors, hence empirical P~m^1.1. Also, installed power typically =2-3x hover power: maximum forward speed and/or performance margin drive design.



$$M_{p\ max} = (1/144\pi)(1/A_m)(P\rho_a/hT_a)^2$$

Hot air balloon performance depends on supplied heat power P and heat transfer coefficient h :a payload maximum exists, regardless of envelope diameter. P=2kW (MMRTG), P=500W (ASRG)-→ light gas

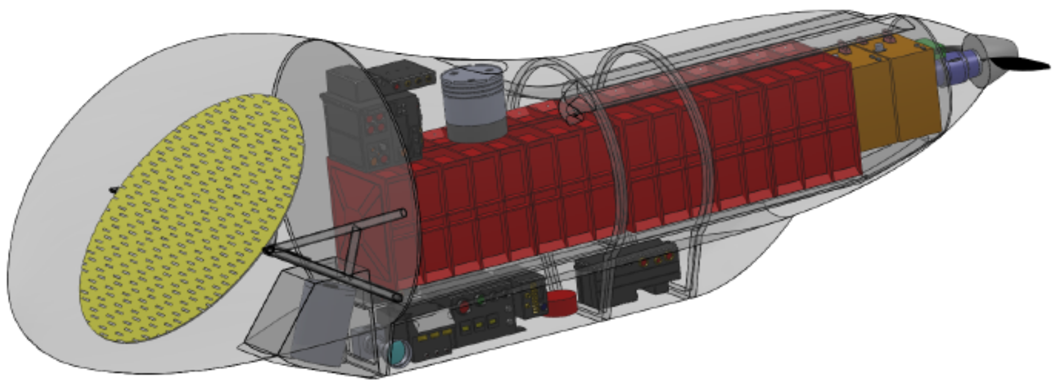
Lorenz, R. D., Linear Theory of Optimum Hot Air Balloon Performance – Application to Titan, The Aeronautical Journal, 112, 353-356, 2008

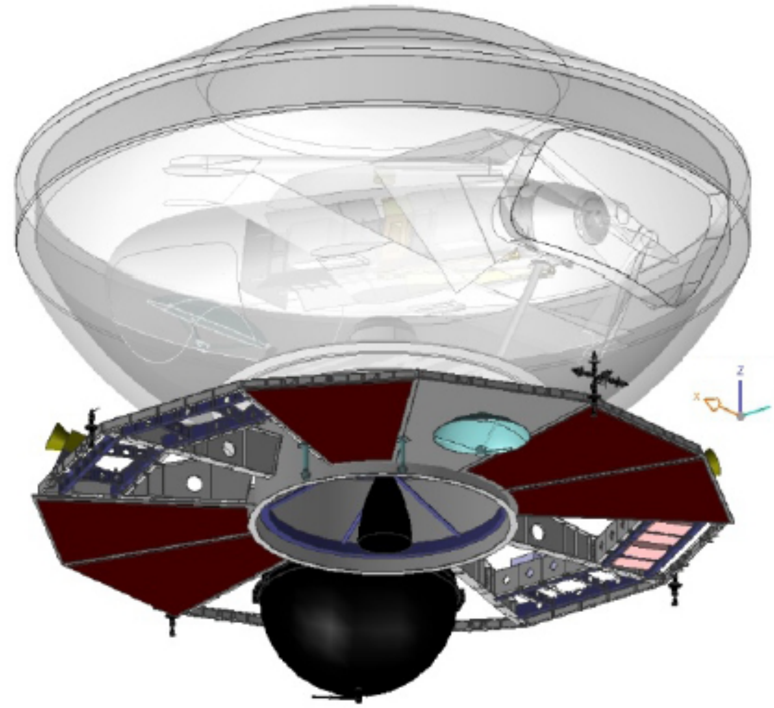
AVIATR – Aerial Vehicle for In-Situ and Airborne Titan Reconnaissance

A Titan Airplane Mission Concept

(enabled by ASRG - power/weight)

Jason W. Barnes · Lawrence Lemke · Rick Foch · Christopher P. McKay · Ross A. Beyer · Jani Radebaugh · David H. Atkinson · Ralph D. Lorenz · Stéphane LeMouélic · Sebastien Rodriguez · Jay



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NASA
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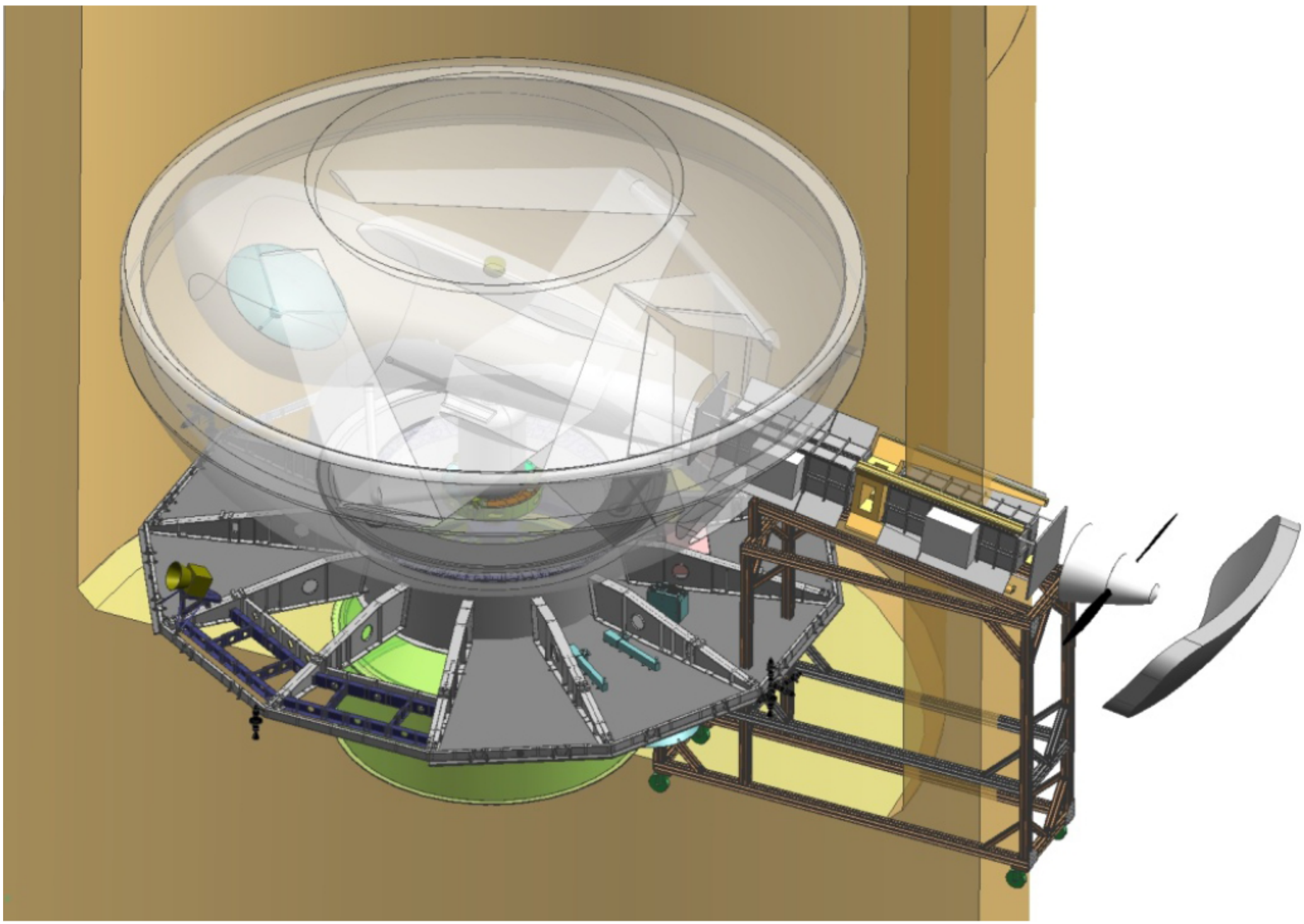
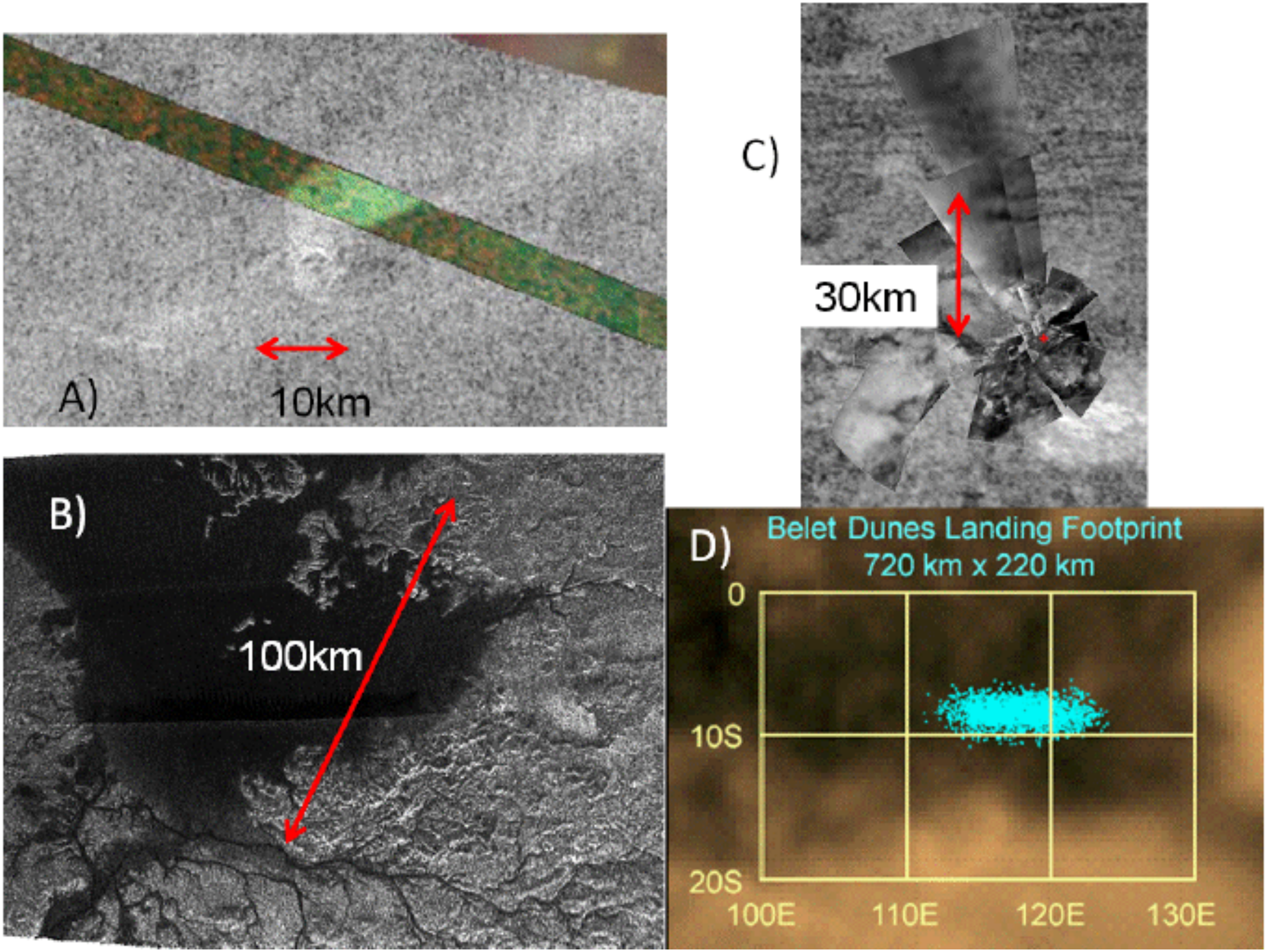




A)
10km
B)
100km
C)
30km
D)
Belet Dunes Landing Footprint
720 km x 220 km
0
10S
20S
100E
110E
120E
130E

Lander-Launched Micro-UAV for Titan Science

USMC has hundreds of Back-packable Dragon Eye UAVs. Mass 2.7 kg. Endurance ~60 minutes on battery. Range ~ 10km. Video to backpack/laptop control station. Cruising speed 35 km/h.

~1kg Titan UAV could fly for several hours (vertical launch off lander) – augments/replaces descent imager landing site context (stereo, λ, lander in scene), plus boundary-layer meteorology profiling.

Can have much smaller wing area in Titan low gravity, thick atmosphere (or could fly 5x slower)

Possible implementation as competed student experiment ?

Lorenz, R. D., Titan Bumblebee : A 1-kg Lander-Launched UAV Concept, Journal of the British Interplanetary Society, 61, 118-124, 2008.

Bumblebee (*bombus*) is a subarctic insect, evolved to exploit periglacial terrain. Note the unaerodynamic appearance with insulating fur.

Bees must have warm flight muscles to fly - warm them before takeoff; do not drain a flower of nectar but only remain as long as muscles stay warm (see B. Heinrich's book 'Bumblebee Economics')

Heat rejection from motor is usual problem for terrestrial vehicles. An exception is a recent autonomous UAV project (British Antarctic Survey/TU Braunschweig) used to study air:surface boundary layer heat fluxes in the Weddell Sea, Antarctica. 45km flights ~ 40 minutes. For small UAVs in cold environment, insulation is required.

In fact insulation/convective heat transfer pathways must be tuned (duct tape.) When adjusted for warm steady-state flight, only 10 mins of static operation on ground will cause batteries to overheat! (Phil Anderson, BAS, Personal communication, 2008)

Explore the minimum useful Titan airplane.

Start with 1kg (we will soon see smaller doesn't make much sense)

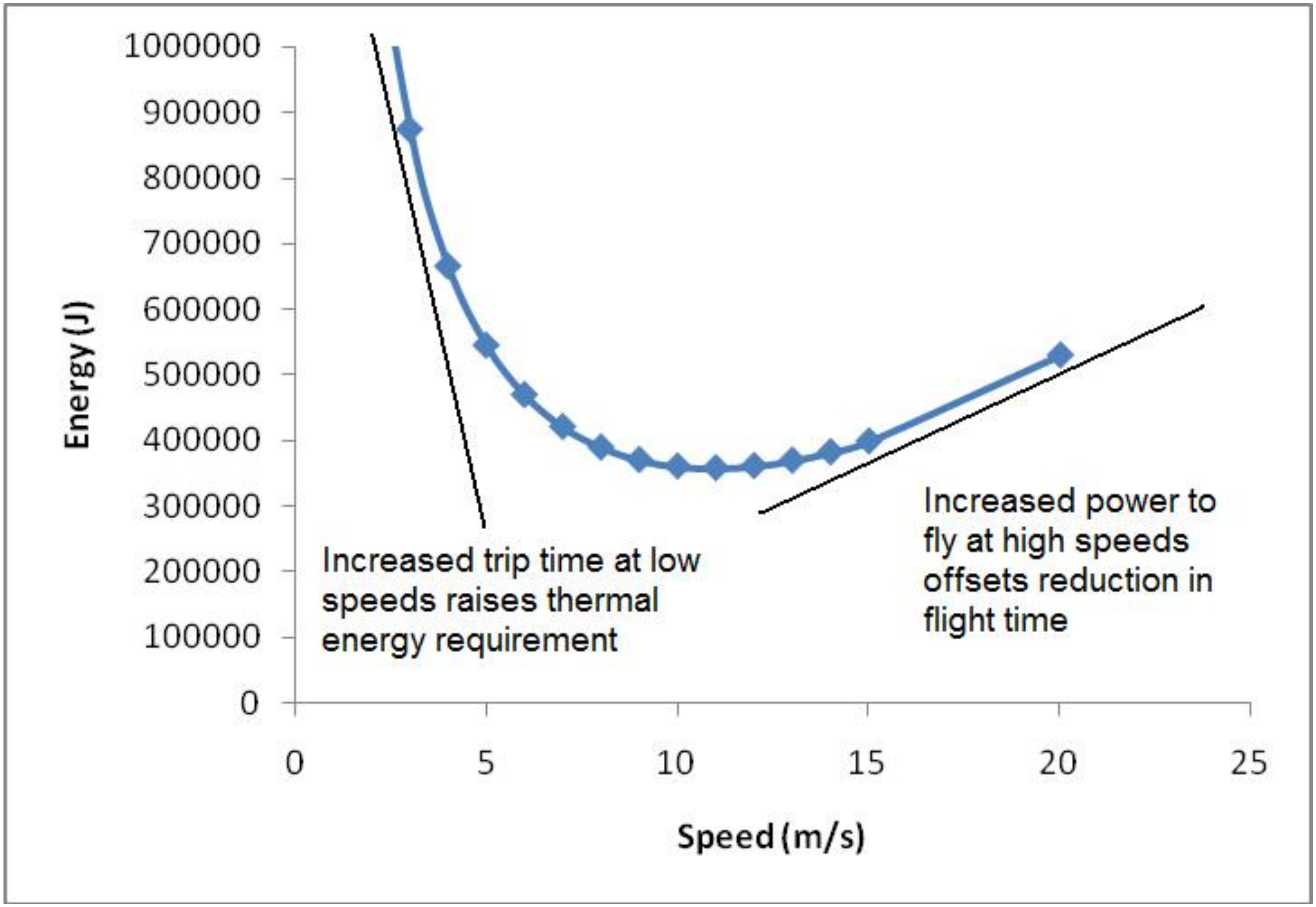
3 Convergent Factors :

Primary batteries (e.g. $LiSOCl_2$, per Huygens, Galileo) have specific energy of ~400 W-hr/kg. If we allocate half of our 1kg to batteries, we have ~200 W-hr (720kJ) This means 200W for 1 hour, or 50W for 4 hours, 10W for 20 hours.

But vehicle must stay warm. 1kg equipment pod with density of ~1000 kg/m^3 has an area of $400cm^2$. If we have a 0.5cm thick layer of foam insulation (Basotect, as on Huygens $k=0.02\ Wm^{-1}K^{-1}$) then with ΔT~200K required in 94K environment, we lose ~30W.

If near-surface winds are ~0.5-1 m/s, we need to fly at several m/s to penetrate. Empirical scaling relationships suggest flight power $P \sim 10.9\ m^{0.8}V^{0.9}(g/g_e)$.
For 1kg at 10m/s in Titan gravity ($g/g_e=1/7$) this means ~15W.

So, 4-6 hour flight seems possible.



Energy requirement to fly 100km

Need to communicate via lander (and use lander as beacon for navigation?)

Horizon distance at Titan for altitudes of 0.1, 1, and 2km altitude is 22, 71 and 101 km away. So we can fly at low altitudes for some tens of km, perhaps 100km away and remain in line-of-sight (ignores multipath, terrain blocking, refraction)

Lander delivery ellipse is ~70x240km 1-sigma, so to fly 100km would be useful (gives good probability of reaching given point in the ellipse)

At 10 m/s, cover 100km in 3 hours.

RF power for 'video' rate telemetry is ~few to ten W (DC).

Flying at 1km, see a swath ~1km wide. With 1m/pix, then 100x1 km long swath, or 10^8 1x1m pixels. In other words, some GB of potentially useful data. Comparable with mosaic from a panoramic camera. (Not worth acquiring more data than this unless have clever data selection or a very good downlink capability..?)

Tradeoffs to explore

Larger UAV - more science capability/range/endurance: probable thermal performance improvement via mass/area scaling. But more cost, volume.

Thicker insulation - lowers thermal energy requirement. But increases aerodynamic drag. Insulation performance ultimately compromised by instrument/propulsion/electrical penetrations and feedthroughs

Slender or stubby. Slender has lower drag but higher heat loss area. Blended wing-body?   Wings ? Or just rotor.

Flight speed. Altitude   (High is safer, easier comms. more area imaged, but lower resolution. Longer path for CH_4 absorption; gas and haze scattering. Profiles desirable for boundary layer meteorology)

Rotor diameter, speed. (Stall for vertical takeoff; tip speed Mach…)

Motor inside insulation or outside ? (~10% of flight power dissipated inside adds to thermal budget, but have shaft feedthrough..)

Guidance

Must fly in daytime (illumination for imaging, plus sun position as a heading reference - remember no GPS, no magnetic field)

Pressure altimeter. Pitot airspeed.

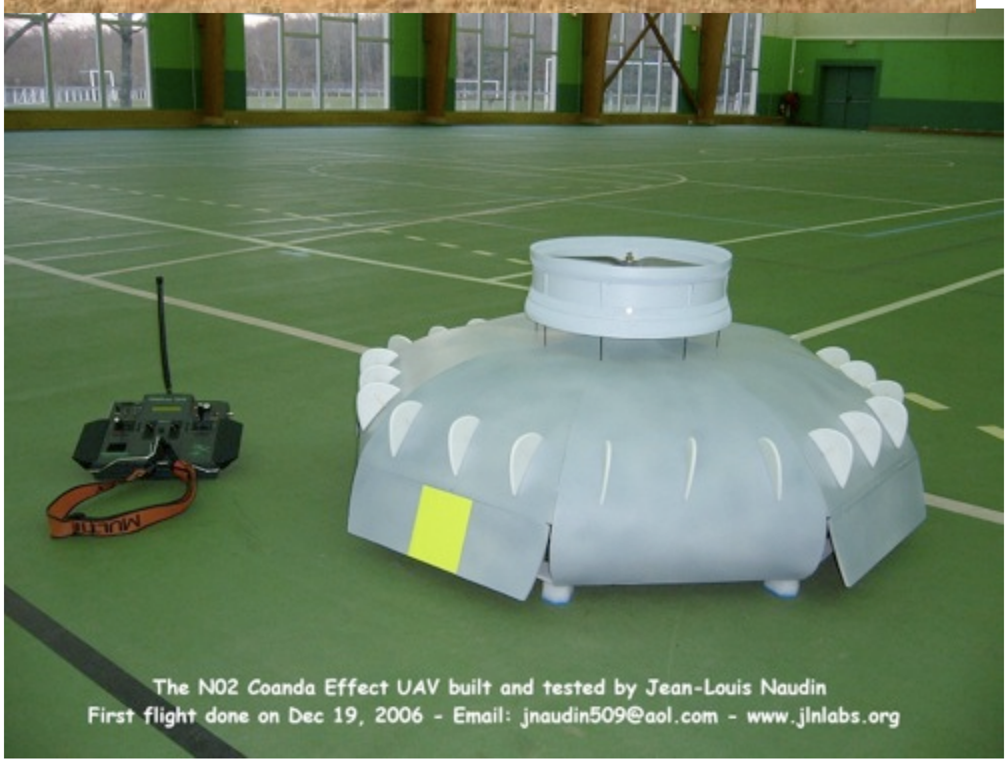
More robust to incorporate additional heading/position reference - use lander as a beacon. UAV antenna systems for emitter location are in use.

(Some less robust but conceivable possibilities - Groundspeed via optical odometry? Inertial guidance? Radar ? Sonar?)

Payload

Nominally Side-looking camera plus meteorology

(heavier variant could consider spectrometer, UV-fluorescence etc. for astrobiology survey of cryolava flows etc.)



Commercial/Military small-scale Ducted Fan UAVs are proliferating.

Ducted Fan obviates rotor hazard, introduces some improvements in controllability.

If we have learned one thing from the history of invention and discovery, it is that, in the long run - and often in the short one - the most daring prophecies seem laughably conservative.

Arthur C. Clarke, The Exploration of Space, 1951